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Research on Digital Protection and Green Exhibition Design of Textile Cultural Heritage Oriented towards Sustainable Development

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Article

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ABSTRACT

The long-term conservation of historic textiles, with their fragile organic fibers and susceptibility to degradation, presents a significant challenge within museum settings. This study investigates an integrated model—the Digital Twin for Sustainable Exhibition (DTSE)—to address the conflict between the physical preservation needs of textile artifacts and the environmental impact of their exhibition. The core thesis is that a high-fidelity digital twin, capturing not only the visual pattern but also the micro-geometry of the weave structure and material condition, serves as a foundational enabler for green exhibition design. The methodology employs a comparative scenario analysis, grounded in Life Cycle Assessment (LCA) principles, to quantify the potential environmental footprint of exhibiting historic silk artifacts, using the China National Silk Museum in Zhejiang as a representative case. Data for traditional exhibitions using MDF and halogen lighting are contrasted with the DTSE model, which minimizes the display of original textiles and utilizes sustainable materials such as bamboo panels and LED lighting. The results indicate that this approach can reduce an exhibition's carbon footprint by an estimated 40–60%, achieved through the strategic reduction of physical display infrastructure and energy loads, while simultaneously mitigating the physical and environmental stresses on the textiles. Consequently, the DTSE model offers a synergistic solution that enhances textile conservation by limiting physical exposure while advancing sustainability. This approach is highly replicable, providing a scalable framework for the preservation of a wide range of historic textiles and other delicate cultural heritage materials.

KEYWORDS

textile, digital preservation, sustainable exhibition, silk

INTRODUCTION

Textile cultural heritage, a vibrant and intricate testament to human creativity and history, is inherently fragile [1]. Organic materials are highly susceptible to degradation from light, humidity, pests, and physical handling. Traditional museum practices, while dedicated to preservation, face a fundamental conflict: the act of exhibition, which is crucial for cultural dissemination and education, often accelerates the deterioration of these delicate artifacts [2]. Moreover, the conventional approach to exhibition design—characterized by climate-controlled environments, extensive use of processed materials for displays, and international loans—carries a significant environmental burden [3,4]. In an era of escalating climate change and resource scarcity, the cultural sector is compelled to re-evaluate its methodologies and align them with the principles of sustainable development [5].

This paper addresses the critical intersection of heritage preservation and environmental responsibility. It moves beyond general advocacy for digital and green solutions to propose and analyze a specific, integrated model: the Digital Twin for Sustainable Exhibition (DTSE) (see Figure 1). This model posits that the creation of a comprehensive, high-fidelity digital twin of a textile artifact is the foundational step that unlocks transformative possibilities for low-impact, green exhibition design. By decoupling the artifact's rich informational and aesthetic content from its fragile physical form, the DTSE model offers a promising approach to the exhibition-preservation dilemma. This research focuses on a precise, refined argument: that digital preservation is not a parallel activity to sustainable exhibition, but its direct enabler. The study provides both quantitative and qualitative analyses to support this thesis, using existing data to build a robust and scientifically grounded argument. To anchor the research in a tangible context, this study references the rich textile heritage of China, with a specific focus on institutions and practices in the Zhejiang region, home to the globally significant China National Silk Museum (CNSM).

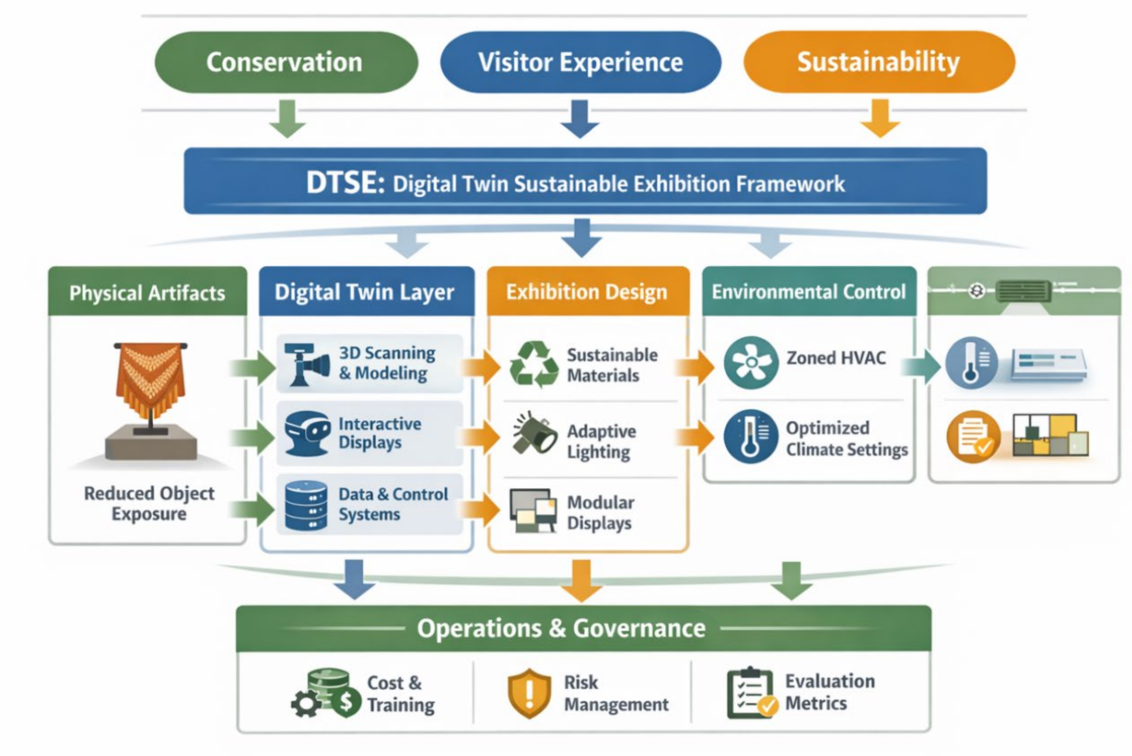

Figure 1. Digital Twin Sustainable Exhibition conceptual framework

LITERATURE REVIEW

The conservation of textile cultural heritage has long been a specialized field, focusing on controlling environmental factors such as light, temperature, and relative humidity to slow the inevitable decay of organic fibers and dyes [6]. The conventional paradigm for museum exhibitions involves stringent environmental controls, often requiring energy-intensive HVAC (heating, ventilation, and air conditioning) systems to maintain a stable microclimate [3]. The environmental cost of such practices is substantial. Furthermore, the materials traditionally used in exhibition scenography, such as medium-density fiberboard (MDF), vinyl graphics, and solvent-based paints, have significant environmental footprints, from production to disposal [7]. Recent studies utilizing Life Cycle Assessment (LCA) methodologies have begun to quantify the environmental impact of museum exhibitions, revealing that material choice, transportation of artifacts, and energy consumption are primary contributors to their carbon footprint [8].

Concurrently, the field of digital preservation of cultural heritage has matured rapidly. Techniques such as high-resolution photography, photogrammetry, and 3D laser scanning now allow for the creation of dimensionally accurate and photorealistic digital replicas—or “digital twins”—of artifacts [9]. These digital twins serve multiple purposes, from scholarly research and archival documentation to virtual reality (VR) experiences and online collections. In the context of textile heritage, digitalization captures not only the visual pattern but also the subtle textural details of the weave, the drape of the fabric, and its material condition, documenting the artifact in a state of arrested decay [10]. Several institutions globally, including prominent museums in China, have embarked on ambitious digitalization projects to safeguard their collections and enhance public access.

The concept of green or sustainable exhibition design has also gained traction, advocating the use of recycled, recyclable, or renewable materials, energy-efficient lighting, and modular designs that minimize waste [7]. Materials such as bamboo panels, water-based paints, and LED lighting are increasingly being adopted [11]. LED lighting, in particular, offers a dual benefit for textile exhibitions: it consumes significantly less energy than traditional halogen lamps and emits negligible levels of UV and IR radiation, which are especially damaging to textiles. While the individual merits of digital preservation and green exhibition design are well documented, a significant gap exists in the literature regarding a systematic, integrated conceptual model that leverages the former to achieve the latter. This paper aims to fill that gap by proposing and evaluating the DTSE model, which treats digitalization as a strategic enabler of sustainable exhibition practices.

METHODOLOGY

This study employs a mixed-method approach that combines a comprehensive review of existing literature and data with a structured case study analysis. The core of the methodology is a comparative scenario analysis, which utilizes established data and principles from the LCA framework to quantify the potential environmental benefits of the proposed DTSE model against a Traditional Exhibition Model (TEM). It is important to clarify that this study does not constitute a formal, product-specific LCA, but rather a conceptual analysis designed to compare the potential impacts of two distinct exhibition strategies. The comparative unit of analysis is the entire exhibition as a holistic system, designed to showcase a specific collection. Therefore, normalization per artifact is intentionally not applied, as the strategic reduction in the number of physical artifacts is the primary independent variable being evaluated in the DTSE model. Comparing the total footprint of each strategy is the most direct method to quantify the overall environmental benefit of the proposed intervention (see Figure 2).

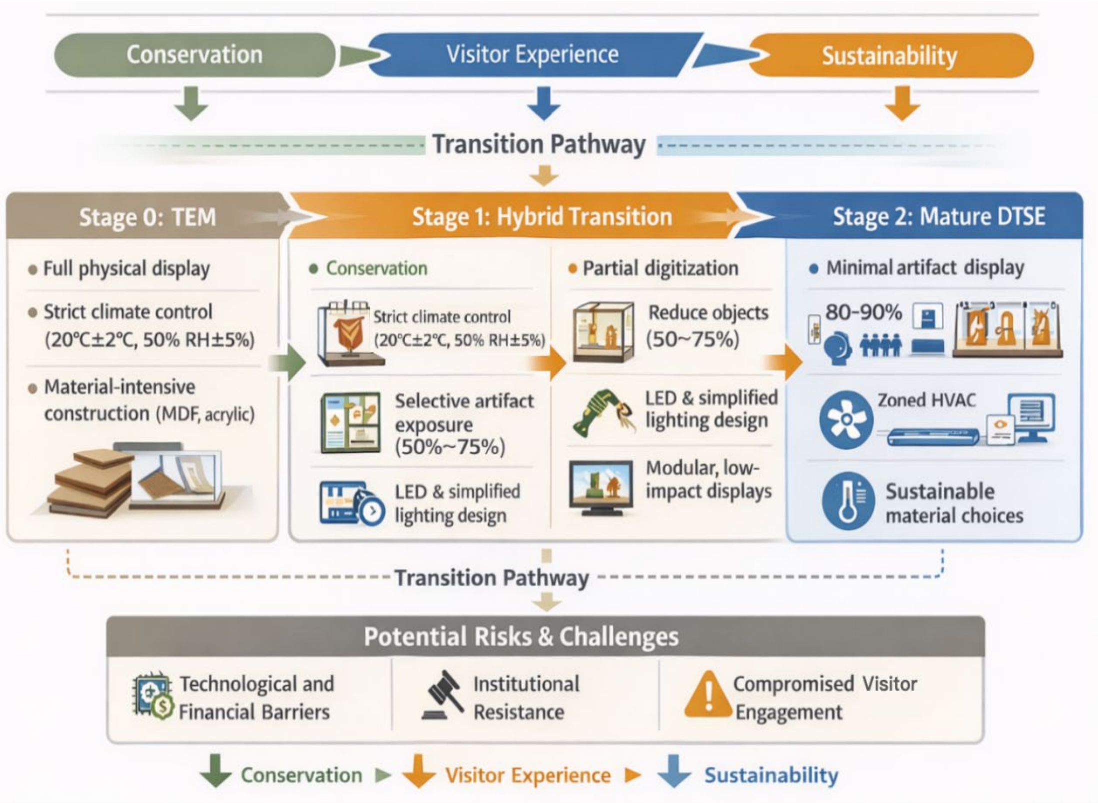

Figure 2. Transition pathway from Traditional Exhibition Model to Digital Twin Sustainable Exhibition

The research is structured in three phases:

- **Model Definition and Data Compilation:** The first phase defines the parameters of two distinct models:
  - **Traditional Exhibition Model (TEM):** A hypothetical but representative textile exhibition (e.g., 200 sq. meters) featuring 50 original artifacts, requiring stringent climate control (20°C ± 2°C, 50% RH ± 5%), traditional lighting (halogen spotlights calibrated to the international textile conservation standard of 50 lux), and display cases and structures constructed primarily from MDF, acrylic, and vinyl. MDF is chosen as a baseline for the TEM due to its ubiquitous use in temporary exhibitions. It is important to recognize that while its production involves energy-intensive processes and chemical binders, MDF often plays a positive role in the circular economy by utilizing recycled wood fibers.
  - **Digital Twin for Sustainable Exhibition (DTSE) Model:** An exhibition of the same scale, but where only 10 of the most robust original artifacts are physically displayed. The remaining 40 are represented through a combination of high-resolution digital interactives (touchscreens,

projections), VR experiences derived from their digital twins, and a small selection of high-quality 3D-printed replicas for tactile engagement. This model utilizes green design principles, including display structures made from bamboo plywood, recycled aluminum, and water-based finishes. Lighting is exclusively LED, and the reduced number of physical artifacts allows for a potential relaxation of energy-intensive climate control in non-artifact zones.

For both models, data on the environmental impact of materials and processes were compiled from established LCA databases (e.g., Ecoinvent) and peer-reviewed studies. This includes data on embodied carbon (kg CO2e) for materials like MDF versus bamboo plywood, energy consumption (kWh) for halogen versus LED lighting per hour of operation, and the carbon footprint associated with the transportation of artifacts.

- **Quantification of Digitalization and Hardware Impact:** A critical component of the methodology is to account for the environmental cost of the digitalization process itself. Data on the energy consumption of high-resolution 3D scanners, photogrammetry rigs, and the associated computational processing and data storage were gathered from manufacturer specifications and academic research. This allows for a more balanced assessment, acknowledging that the digital component of the DTSE model is not without its own environmental footprint. The energy consumption is calculated for the one-time creation of the digital twins, which can then be reused for multiple exhibitions and purposes. To address the operational energy and embodied carbon of high-power playback devices (e.g., 4K projectors, VR headsets) utilized in the DTSE model, this study incorporates two critical correction factors into the LCA boundary conditions:
    - **Asset Amortization Strategy:** Unlike MDF display structures, which are often single-use waste, digital hardware is classified as reusable capital infrastructure. Its embodied carbon is not attributed to a single exhibition but is amortized over a standard 5-year operational lifespan across multiple exhibition cycles.
    - **Smart Duty Cycling Model:** An on-demand energy consumption model is applied. The calculation assumes that digital exhibits utilize motion sensors to enter low-power standby modes (consumption < 5 W) when inactive. Based on typical museum visitor flow analysis, an effective duty cycle of 30% is applied for high-power active states, whereas traditional lighting models assume 100%

continuous operation during opening hours.

- **Case Study Analysis—The CNSM Context:** To ground the theoretical models in a real-world context, this research utilizes the CNSM in Hangzhou, Zhejiang, as a focal point. While direct experimental data from the museum are not generated, the study draws upon CNSM's well-documented leadership in both textile conservation and digital initiatives. Consequently, the quantitative results presented in this paper should be interpreted as illustrative estimations to demonstrate the model's potential, rather than a precise environmental audit of the museum's actual operations. The primary purpose of referencing the CNSM is to establish the practical relevance and feasibility of the proposed DTSE model within a real-world institutional context. Information on their collections, exhibitions, and published digital projects is used to inform the assumptions within the TEM and DTSE models. Zhejiang Province, as a historic and contemporary hub of textile production and innovation, provides a rich backdrop, underscoring the relevance and potential applicability of the research. Ultimately, this case study utilizes the museum's specific context as a realistic scenario to illustrate the practical implications and potential benefits of adopting the DTSE model within a leading Chinese cultural institution.

The final analysis synthesizes these data points to compare the total estimated carbon footprint of a single exhibition cycle (e.g., three months) for both the TEM and DTSE models, providing a quantitative basis for the paper's conclusions.

RESULTS

The comparative analysis of the TEM and the DTSE model reveals significant potential for environmental impact reduction through the integrated application of digital preservation and green design principles. The following quantitative estimates, derived from a synthesis of LCA literature and databases, are intended to illustrate the comparative scale of environmental impact rather than to serve as a definitive audit of a specific, real-world exhibition. The data, aggregated and analyzed according to the methodology, provide quantitative support for the central thesis of this paper.

Material-Related Carbon Footprint: The choice of construction materials for display cases, partitions, and informational panels is a major determinant of an exhibition's embodied carbon. For a hypothetical 200 sq. meter exhibition space, the TEM, relying heavily on MDF, would generate an estimated embodied carbon footprint from materials alone in the range of 2,500–3,500 kg CO2e. This analysis focuses on the embodied carbon footprint, though it is acknowledged that a complete comparison would be more complex; for instance, many MDF products contribute positively to the circular economy by utilizing wood waste, a factor not captured in this specific metric. In contrast, the DTSE model, utilizing bamboo plywood and recycled aluminum framing, demonstrates a substantially lower footprint, estimated at 1,000–1,500 kg CO2e. This represents a reduction of approximately 50–60% in the embodied carbon of the scenography, as visually detailed in Figure 3. This saving is attributed to two factors: the significant reduction in total material mass (dematerialization) resulting from fewer physical display structures, and the lower embodied carbon intensity of bamboo and recycled aluminum compared to MDF.

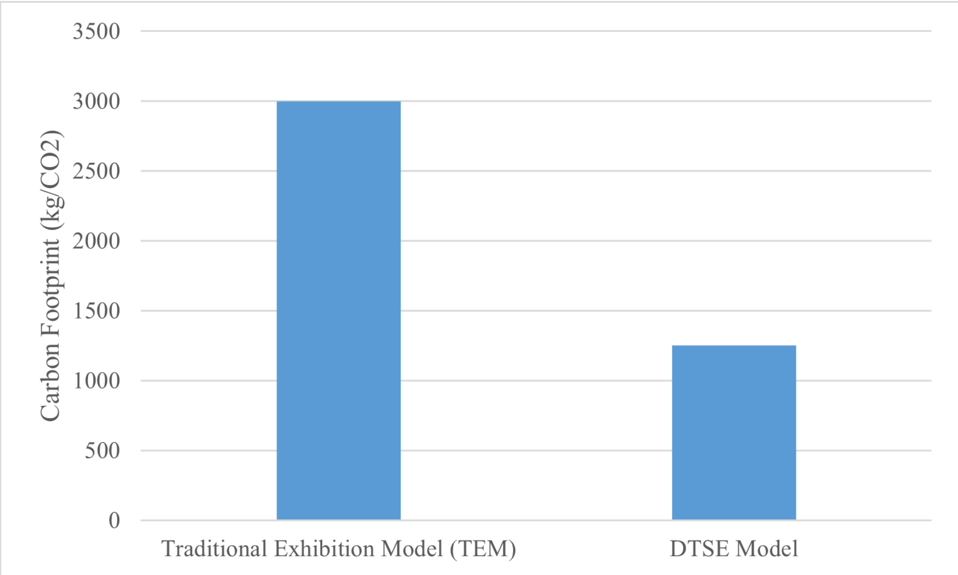

Figure 3. Carbon Footprint from Exhibition Materials

Energy Consumption from Lighting and Climate Control: Lighting is a continuous source of energy consumption throughout an exhibition's duration. Over a three-month exhibition period (approximately 1,000 hours of operation), the TEM's reliance on halogen spotlights would result in an estimated energy consumption of 4,000–5,000 kWh.

To isolate the impact of the "digital twin strategy" from the "lighting technology upgrade," a stepwise decomposition analysis was performed:

Step 1: Technological Efficiency (Hypothetical): If the TEM were merely retrofitted with LED lighting while maintaining 50 physical artifacts, the consumption would drop to an estimated 1,000–1,200 kWh. This indicates that the initial efficiency gain is primarily technological.

Step 2: Structural Reduction (DTSE Strategy): The DTSE model maintains this low energy profile (800–1,200 kWh) but achieves it through absolute reduction of fixture count. By removing 80% of the physical artifacts, the model eliminates the need for 40 sets of focused conservation lighting.

Consequently, while the raw energy data for lighting appear similar between a "modernized TEM" and the DTSE model, the DTSE strategy fundamentally alters the energy structure. It shifts the load from rigid, heat-generating display spots to flexible ambient lighting, which directly facilitates the more significant HVAC savings discussed below. Furthermore, by reducing the number of highly sensitive physical artifacts on display from 50 to 10, the DTSE model allows for a more zoned approach to climate control. While the core area with the 10 artifacts would require strict HVAC control, the larger digital-interactive zones could operate within a wider and less energy-intensive environmental band. This could yield an additional 10–20% reduction in the total HVAC energy load, which is often the single largest contributor to a museum's operational carbon footprint. It must be acknowledged, however, that implementing such a zoned system is a significant assumption. The upfront cost and technical complexity of retrofitting or designing a building with multi-zone HVAC could be substantial and require a separate feasibility analysis. Therefore, this estimated saving should be viewed as a potential long-term benefit for new constructions or major renovations rather than an immediate outcome for all institutions.

Impact of Digitalization: The energy footprint of the DTSE model comprises two digital components: the one-time creation of the digital twins and the operational energy of the interactive hardware. Based on the smart duty cycling model defined in the methodology, the combined energy consumption for 3D scanning (initial creation) and the operation of projectors and VR units (intermittent run-time over three months) is estimated to be between 400–600 kWh. While this represents a specific energy expenditure, the high-efficiency sleep modes of modern display hardware significantly mitigate the operational load. Furthermore, the creation of the digital twin represents a one-off capital investment. Unlike physical consumables, this digital asset is amortized over a long-term lifecycle, as it can be reused for multiple exhibitions and educational purposes without incurring significant additional production energy (see Figure 4).

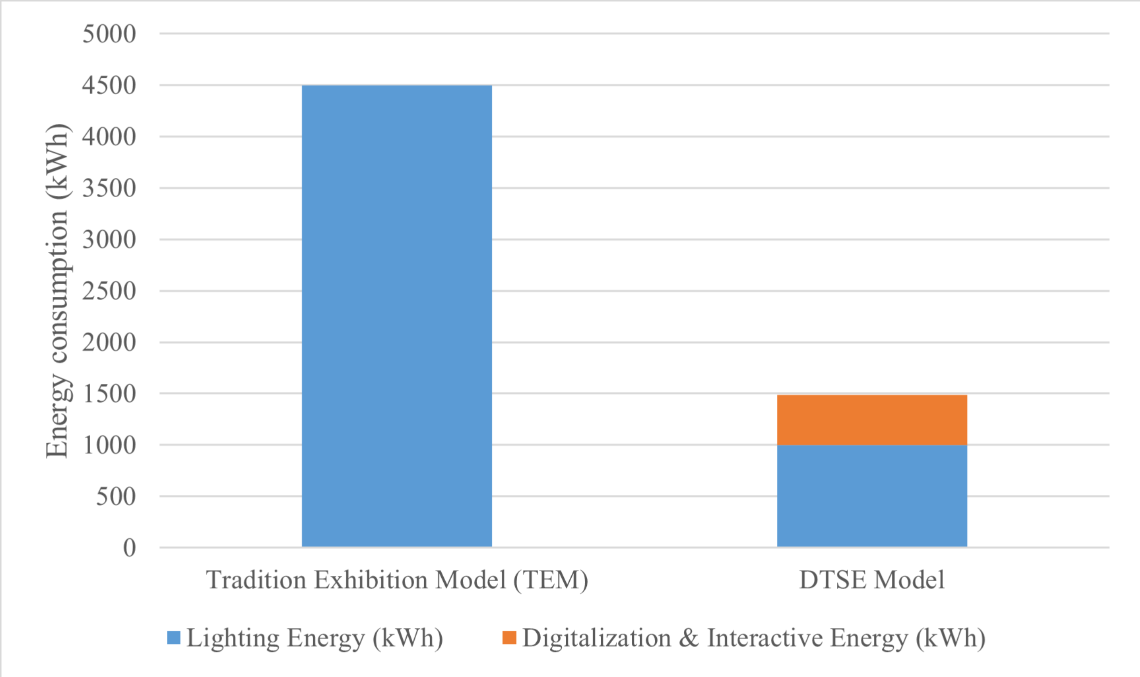

Figure 4. Energy Consumption Comparison Over a Three-Month Exhibition

Overall Carbon Footprint Reduction: Synthesizing these major components—materials, lighting, and climate control—the total estimated carbon footprint for a three-month exhibition under the TEM is projected to be in the range of 8–10 tonnes of CO2e. It is critical to note that the overall footprint includes the energy consumption from the HVAC system, which, as previously mentioned, is often the single largest contributor to a museum's operational carbon footprint. The DTSE model, even after accounting for the energy cost of digitalization, is projected to have a footprint of 3–5 tonnes of CO2e. This constitutes an overall reduction of 40–60%. This result quantitatively demonstrates that strategically substituting physical exhibition components with high-quality digital surrogates, combined with sustainable material choices, offers a robust pathway to minimizing the environmental impact of showcasing textile cultural heritage. Table 1 provides a comprehensive summary of the key metrics and comparative results for both the TEM and DTSE models. The context of institutions like the CNSM, which already possess advanced conservation and digitalization capabilities, suggests that the implementation of such a model is not only theoretically sound but also practically feasible.

Table 1. Summary of Key Metrics for Exhibition Models

Metric	Traditional Exhibition Model (TEM)	Digital Twin for Sustainable Exhibition (DTSE) Model
Number of Physical Artifacts	50	10
Primary Exhibition Materials	MDF, acrylic, vinyl	Bamboo plywood, recycled aluminum
Lighting Type	Halogen spotlights	LED
Material Carbon Footprint (kg CO2e)	2,500–3,500	1,000–1,500
Lighting Energy (kWh, 3 months)	4,000–5,000	800–1,200
Digitalization & Interactive Energy (kWh)	N/A	400–600 (creation + operation)
Overall Carbon Footprint (tonnes CO2e, 3 months)	8–10	3–5

Note: The comparison reflects the current standard practice (halogen for TEM). Sensitivity analysis (see Results) indicates that even if TEM were upgraded to LED lighting, the DTSE model would still maintain a structural energy advantage (approximately 80% reduction in fixture count) due to the reduced number of physical artifacts.

DISCUSSION

The results of this study present a compelling case for the adoption of the DTSE model. The quantitative analysis demonstrates that a synergistic approach, where digital preservation is not just an archival afterthought but a core strategic component of exhibition planning, can lead to substantial and measurable reductions in environmental impact. This finding challenges the traditional curatorial paradigm that prioritizes the display of the original object above all else, suggesting that a hybrid approach can achieve the dual goals of cultural dissemination and environmental stewardship, although careful design is required to ensure the visitor experience is not compromised.

The implications of the DTSE model extend beyond carbon footprint reduction. By minimizing the physical display of fragile textiles, the model inherently enhances their long-term preservation. Each time an artifact is exposed to light, handled for mounting, or subjected to micro-fluctuations in the environment, it undergoes irreversible damage. The DTSE model drastically reduces these risk factors. The tenet of preservation through documentation is elevated to “preservation through virtualization.” In this context, institutions like the Shanghai Museum or the CNSM in Zhejiang, with their vast and invaluable collections, could leverage this model to showcase a greater variety of their holdings through rotating digital features, while keeping the most fragile pieces in optimal, stable storage conditions. The digital twin becomes a high-fidelity proxy, offering forms of engagement—such as magnified inspection of weave structures or virtual try-ons of historical garments—that are impossible with the original artifact behind glass.

However, the implementation of this model is not without its challenges. There is a need for significant upfront investment in digitalization equipment and skilled personnel, as well as potential infrastructure upgrades, such as the sophisticated zoned climate control systems required to realize maximum energy savings. The energy consumption and electronic waste associated with digital technologies must be carefully managed to avoid simply replacing one form of environmental impact with another. Specifically, the long-term environmental cost of digital storage presents a significant challenge. While this study accounts for the one-time energy expenditure of creating the digital twins, a complete life-cycle analysis must also include the perpetual energy required to maintain and cool the data centers that house these assets. Addressing the sustainability of digital infrastructures is therefore a critical and complex issue that requires further research and robust institutional strategies for data management. A critical consideration, which lies outside the scope of this paper’s environmental analysis, is the impact of the DTSE model on the visitor experience. While this model proposes new forms of engagement through high-fidelity digital interactives, its success is ultimately dependent on audience reception. Key metrics for a holistic evaluation—such as changes in visitor numbers, visitor satisfaction surveys, and the measurement of educational outcomes—have not been addressed in this study and represent a crucial avenue for future interdisciplinary research. The challenge lies in balancing the aura of the authentic object, which remains a powerful draw, with the immersive potential of digital surrogates. Therefore, the implementation of the DTSE model must be coupled with a robust visitor evaluation framework to ensure that sustainability goals do not detract from the museum’s core mission to engage and educate the public. While studies have shown high levels of engagement with well-designed digital interactives, the unique aura of the original object remains a powerful draw. The DTSE model does not advocate for the complete replacement of physical artifacts but for a more thoughtful and sustainable balance. The inclusion of a small number of original masterpieces alongside their digital counterparts can serve to anchor the exhibition in authenticity while leveraging the versatility and accessibility of the digital format. This approach allows for a best of both worlds scenario, where the museum's role as a keeper of authentic objects is honored, and its responsibility as a sustainable public institution is addressed. A key limitation of this study is that its quantitative analysis is based on established, yet generalized, LCA data rather than direct empirical measurements from the CNSM. Therefore, the specific carbon footprint reduction figures are projections intended to demonstrate the scale of potential impact. Future research should aim to validate this model by conducting a detailed, site-specific LCA on an actual exhibition at a partner institution. Such a study would provide more precise, verifiable data and further strengthen the case for adopting the DTSE model more broadly.

CONCLUSION

This research has proposed and evaluated an integrated model for the digital preservation and green exhibition of textile cultural heritage, suggesting that a synergistic approach could lead to significant reductions in environmental impact while simultaneously enhancing artifact preservation. The comparative scenario analysis, which applies data from the LCA framework, indicates that the DTSE model can reduce the carbon footprint of a typical textile exhibition by an estimated 40–60%. This is achieved by strategically leveraging high-fidelity digital twins to reduce the number of physically displayed artifacts, which in turn enables the use of green exhibition materials and a substantial decrease in energy consumption from lighting and climate control.

The study, contextualized with reference to the rich textile heritage of regions like Zhejiang and leading institutions such as the CNSM, underscores the practical feasibility of this model. It encourages a shift in perspective from viewing digital preservation and sustainable design as separate initiatives to recognizing them as deeply interconnected components of a holistic, future-oriented museum practice. The digital twin is not merely an archival image but a dynamic asset that offers the potential for new forms of engagement, research, and exhibition, liberating the fragile original from the damaging stresses of constant display. Crucially, the principles of the DTSE model are potentially adaptable for application beyond the specific domain of textiles. The methodology of creating digital twins to enable reduced physical exhibition and promote green design is directly applicable to a vast array of other sensitive cultural heritage artifacts, including manuscripts, prints, watercolors, and ethnographic objects made from organic materials. By embracing such integrated models, cultural institutions worldwide can continue to fulfill their vital mission of preserving and sharing human history while actively contributing to a more sustainable future. This research provides a conceptual framework for this critical transition, offering a potential direction for the museum of the 21st century. While the findings are based on a theoretical model, this study lays the groundwork for future empirical research to validate and refine these principles in practice.

Author Contributions

Hailong Liu and Weiping Lu designed, collected and analyzed the data, and drafted the manuscript. Hailong Liu and Weiping Lu conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Hailong Liu participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Conflict of Interest

The author declares no conflict of interest.

Availability of Data and Materials

The datasets used and/or analysed during the current study were available from the corresponding author on reasonable request.

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