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Integrating Digitized Pattern Reading and Digital Twins for Intangible Cultural Heritage

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Structure

Abstract

In recent years, the limited focus on digitally preserving and integrating traditional patterns has resulted in their diminished visibility and utility, endangering their continuity within cultural memory and stalling interdisciplinary progress across art, history, and the digital humanities[1].[2]

Furthermore, a significant challenge in contemporary literacy is the increasing cognitive resistance toward long-form narratives and complex historical data, a shift in information processing that prioritizes fragmented content over sustained engagement with cultural assets. [3]This study addresses these issues by exploring the integration of intangible and tangible cultural heritage into contemporary contexts through immersive digital technologies. Traditional motifs function as significant carriers of identity and artistic expression, operating as embedded semiotic structures that elicit emotional and cognitive connections to heritage[4].

The research employs a multi-faceted methodology across two scales: a macro-level analysis of traditional patterns from selected global regions and a micro-level application involving the redesign of specific architectural spaces.

The novelty of this research lies in its methodological shift toward Digital Twin technologies and three-dimensional modeling to generate innovative reinterpretations of historical motifs.

The expected outcome is the development of reconfigured traditional patterns that can be effectively reused within digital and contemporary application domains.

By reimagining public and private spaces as immersive, intercultural environments, this study aims to bridge the gap between historical preservation and the rising public preference for entertainment-oriented engagement[5].

Ultimately, the research proposes a sustainable model for museums, heritage sites, and academic institutions to maintain cultural identity while embracing technological innovation.

Keywords: Cultural Heritage, Digital Twins, Traditional Patterns, Environments, preservation

[1] Niu, 2025, p. 12
[2] Wang, Sheng, and Ghani 2025, p. 14
[3] Wolf, 2018, p. 3-6
[4] Galani & Vosinakis, 2024, p. 19
[5] Gao et al. 2024, p. 26-27

Introduction

In recent years, the limited focus on digitally preserving and integrating traditional patterns has resulted in their diminished visibility and use, endangering their continuity within cultural memory and impacting interdisciplinary research across art, history, and digital humanities on a global scale scale.[6] [7]

As traditional patterns and motifs function as significant carriers of cultural identity and artistic expression, their visual and symbolic complexity conveys historical narratives and belief systems, operating as embedded semiotic structures that elicit emotional and cognitive connections to place and heritage[8].

Engagement with these patterns facilitates processes of recognition, reflection, and intergenerational continuity; however, to ensure the sustainability of this digital content, it is essential to keep up with the rapid changes in technology[9].

This can be accomplished by using consistent and interoperable data models that allow for the seamless migration of heritage data into contemporary design frameworks[10].

Advancements in immersive digital technologies and increasingly accessible digitization methods have created new opportunities for the integration of both intangible and tangible cultural heritage into contemporary contexts [11].

This thesis is dedicated to the development of a sustainable methodology for the revival of traditional patterns using Digital Twin technology to reimagine public and private spaces as immersive, intercultural environments. It discusses the emergence of the Digital Twin, which synchronizes with physical data to monitor degradation and guide [12]restoration[13].

The methodology for this study is multi-faceted, combining theoretical research with practical digital modeling and AI-assisted synthesis.[14]

The novelty of this research lies in its methodological approach, which employs three-dimensional modeling of traditional patterns to generate innovative reinterpretations that maintain a connection to cultural identity while embracing technological innovation.

The case study explores two distinct sections from a macro to micro vision: first, the traditional pattern lineages from the chosen countries, and second, the different spatial areas that can be redesigned with them.[15]

[6] Tian, Liu, and Lu 2024, p. 7
[7] Niu, 2025, p. 1
[8] Galani & Vosinakis, 2024, p. 17-18
[9] Jouan & Hallot, 2020, pp. 2–4
[10] Asriana and Khidmat 2024, p. 5
[11] Niu, 2025, pp. 45–48
[12] Matta 2024, p. 11
[13] Jouan & Hallot, 2020, pp. 5–6
[14] Niu, 2025, p. 15
[15] Ivi, pp. 8–10

Data for the analysis were acquired through a review of historical practices, such as the mathematical logic of Safavid-era motifs[16], and an evaluation of current industrial applications of Digital Twins in fields like smart manufacturing, healthcare, and urban infrastructure[17].

Following these evaluations, the most suitable solutions for spatial integration and participatory engagement were identified to address the rising public disregard for historical objects[18].

The thesis then illustrates the process of "structural mapping," presenting the result in high-fidelity simulations that serve as a bridge between ancient craftsmanship and future-oriented [19]technology[20].

Here, in this thesis, there will be the first steps of prototyping to have first samples of 2D designs, to develop them in future directions combined with digital twin,

[16] Rezazadeh, 2024, pp. 112–115
[17] Grieves & Vickers, 2017, pp. 85–113; Batty, 2018, pp. 317–320
[18] Manzo & Devine-Wright, 2013, pp. 45–50
[19] Habib and Alam 2024
[20] Moretti, 2013, pp. 103–120

Research Questions:

1. How can parametric translation effectively revive traditional motifs within contemporary art and visual design?

The most effective strategy for reviving traditional patterns lies in a shift from passive replication to "active reinterpretation." This involves a deconstructive methodology where motifs are analyzed for their foundational geometric and semiotic logic. By identifying these core "visual grammars," patterns can be reconstructed as dynamic digital assets that maintain their cultural "DNA" while adapting to contemporary artistic mediums, canvas dimensions, and digital display environments.

2. To what extent is the implementation of large-scale design projects feasible?

While large-scale heritage projects are often hindered by high costs and physical constraints, the use of Digital Twin technology provides a feasible pathway for implementation. By creating high-fidelity virtual replicas, designers can simulate the impact of intercultural patterns on urban environments before physical resources are committed[21]. This significantly reduces material waste and allows for the testing of complex spatial layouts in a risk-free virtual environment.

To bridge the gap between large-scale digital feasibility and real-world urban constraints, several landmark projects serve as operational benchmarks:

- The Notre-Dame de Paris Reconstruction: Following the 2019 fire, pre-existing high-fidelity 3D digital twins and architectural scans became the primary framework for directing structural restoration. This project demonstrates how large-scale digital replicas function as risk-free environments to guide massive physical reconstructions without wasting material resources.
- The Genoa Enheritage Project: Focused on the UNESCO-listed Le Strade Nuove and Sistema dei Palazzi dei Rolli, this project integrates IoT sensors and satellite data directly into a dynamic digital twin. It allows city planners to simulate the impact of environmental factors and mass tourism on historic facades before deploying real-world conservation teams.
- The Kalasatama District (Helsinki): This urban-scale pilot digital twin is actively used to simulate spatial transformations and test how newly integrated designs synchronize with climate data, lighting conditions, and existing urban morphology before physical execution.
- The Historic Cairo Documentation Project: Utilizing laser scanning and Digital Twin architectures on historical structures like Al-Mu'izz Street, this initiative creates replicable

[21] Batty, 2018, pp. 317-320

digital environments. It tests the structural and aesthetic integration of architectural heritage assets before implementing physical restoration on-site[22].

3. Which approaches or expertise are most effective in the redesign of traditional patterns?

The redesign of traditional patterns is most effective when it bridges the gap between computational design and humanities-based expertise. While AI-driven tools can handle the technical synthesis of patterns, a "Human-in-the-loop" approach ensures that the resulting designs act as "cultural anchors" rather than mere decoration[23]. This synthesis of historical knowledge and modern software allows for a redesign process that is both technically innovative and culturally authentic[24].

4. What techniques can best address time constraints in the design process?

In the professional design process, time constraints are best addressed through parametric and generative modeling. By establishing mathematical rules for traditional motifs, designers can generate thousands of iterations in seconds. This allows the researcher to spend less time on manual drafting and more on the qualitative assessment of how these patterns resonate emotionally and spatially[25].

5. How can public engagement be fostered to enhance connections with newly redesigned patterns and spaces?

Public connection to newly redesigned spaces is fostered by moving the community from passive observers to active participants. Utilizing Digital Twin platforms as a collaborative tool allows stakeholders to visualize and influence the design in real-time. This participatory approach directly addresses the psychological challenge of Place Attachment, ensuring that new designs are not seen as "alien" interventions but as an evolution of the community's collective identity.[26]

[22] Shen et al. 2025, p. 18
[23] Moretti, 2013, pp. 112-115
[24] Wesnina, Prabawati, and Noerharyono 2025, p. 33
[25] Niu, 2025, pp. 12-15
[26] Manzo & Devine-Wright, 2013, pp. 45-50

1. State of the art

In the contemporary scholarly discourse surrounding cultural heritage, a critical crisis has emerged regarding the preservation of traditional semiotic structures. These structures are defined as the organized systems of symbols and visual grammars, such as the specific geometric logic of Islamic tiling or the narrative iconography in Andean textiles, where the arrangement of motifs conveys specific cultural meanings.

In recent years, a limited focus on the digital preservation and integration of these patterns has resulted in their diminished visibility and practical utility. This trend does not merely represent a loss of aesthetic data; it actively endangers the continuity of cultural memory. By failing to digitize the "logic" behind these patterns rather than just their appearance, we negatively impact interdisciplinary research across art, history, and the digital humanities on a global scale. [27] [28]

A shift in cognitive engagement further compounds this crisis, reflecting a broader systemic challenge identified across various disciplines. As global audiences migrate toward fragmented, entertainment-oriented digital consumption, there is a marked decline in sustained interaction with complex historical and semiotic narratives. This "cognitive fragmentation" mirrors concerns in literary sociology, where the move away from close reading toward rapid data consumption threatens our ability to parse deep-time cultural structures.

In this architectural and digital humanities context, "close reading"—traditionally understood as the intensive, methodical analysis of an artifact to uncover its layered meanings, formal patterns, and historical nuances- is treated as a necessary cognitive faculty. When applied to spatial design, close reading represents the user's capacity to deliberately decode the rich mathematical, symbolic, and structural narratives embedded within traditional motifs, rather than processing them as mere superficial decoration[29].

The erosion of this practice means that modern viewers increasingly consume heritage patterns as fleeting, aestheticized background noise[30]. Consequently, this research establishes a vital baseline criterion: the proposed Digital Twin environments must transcend passive visual display, utilizing immersive spatial structures to actively re-engage the viewer's cognitive faculties, thereby cultivating

[27] Yang, Fenghu and Xiaodong 2011, p. 41-43
[28] Niu, 2025, pp. 3-5
[29] Burgio, Buzzoni and Simion 2024, p. 8-10
[30] Niu, 2025, p. 16

a digital-spatial equivalent of close reading that restores deep-time historical legibility to contemporary public [31]spaces[32].

Within the digital humanities, this issue is exacerbated by a technical gap: the inability to effectively quantify and synthesize intricate character dynamics alongside emotional trajectories. This limitation has stalled the development of unified computational visualizations—tools that could potentially reconcile the structural complexity of ancient motifs with the rapid-fire cognitive habits of modern audiences. By failing to bridge this gap, scholarly engagement remains siloed, unable to translate historical depth into a medium that resonates with the contemporary digital [33]landscape.[34]

The methodology concludes with an evaluation phase focused on "Identity Reviving." By synthesizing the 11-step process from input data to Digital Twin implementation, the research aims to engage audiences through visual exhibitions and digital displays. The final output is not merely a design but an immersive environment that maintains a connection to cultural identity while embracing contemporary innovation.

This 11-step operational workflow consists of the following consecutive stages: (1) historical data acquisition and archival research, (2) morphological extraction of traditional motifs, (3) vectorization and high-resolution digitization, (4) parametric modeling and geometric optimization, (5) multi-spectral material and texture mapping, (6) spatial syntax and environmental analysis of the target site, (7) digital data layering and mesh synthesis, (8) AI-assisted pattern synthesis and scale adaptation, (9) Digital Twin real-time engine integration, (10) immersive spatial layout projection, and (11) participatory public interaction and feedback loop execution[35].

The final output generated by this structured pipeline is not merely a design but an immersive environment that maintains a connection to cultural identity while embracing contemporary innovation, evaluating how "responsive data organisms" can sustainably project heritage aesthetics into contemporary public [36]spheres[37].

[31] Minerva 2024, p. 20-22
[32] Manovich, 2001, pp. 218–222
[33] Bruno, Sabatino, and Tomasi 2025, p. 63
[34] Moretti, 2013, pp. 103-120
[35] Niu, 2025, pp. 45–58
[36] Daquino et al. 2022, p. 8
[37] Manovich, 2001, pp. 211–214

The aligned activities are listed:

1. Decolonizing Physical Spaces through Digital Twins

I attended the workshops and sessions with the Atlas project. It was a collaborative multi-university research initiative that brought together the University of Bologna, Ca' Foscari University of Venice, the University of Turin, and the University of Pavia. Also, the final session of this project, which was in Venice, with speakers, Prof, Marilena Daquino and Marina Buzzoni, The use of visual communication to fight uniform, monocultural global design finds a powerful, real-world benchmark in the PRIN ATLAS project. This major, multi-university research workshop explicitly utilizes advanced digital documentation and spatial visualization to study, map, and preserve architectural and environmental heritage across regional landscapes. This thesis operates in the exact same context but pushes the methodology into an active design phase; by utilizing digital twins as an experimental, virtual canvas to test, redesign, and weave traditional motifs back into daily life, the project directly develops the spatial and heritage preservation goals established by the ATLAS collaboration.

2. The Aesthetics of Digital Replicas

The artistic and philosophical investigation into how virtual environments, lighting, and digital textures alter our perception of an artwork's "aura" directly extends the theoretical work established by the Venice Centre for Digital and Public Humanities (VeDPH) and its flagship open platform, *magazén*. Existing research published through this benchmark frames digital reconstruction not merely as a technical or visual copy, but as a rigorous, public-facing scholarly hypothesis and a core interpretive methodology. This thesis operationalizes that exact philosophy; by evaluating how translating hand-drawn, material Persian and Italian motifs into a 3D digital ecosystem changes their expressive meaning, the project directly advances VeDPH's established framework of treating the digital replica as a brand-new visual language.

3. Human Relations, Social Justice, and Inclusion

When examining how the globalization of modern architecture causes a loss of local cultural identity and public disregard for heritage, this project aligns directly with established benchmarks in the digital humanities that treat data collection as an act of cultural sustainability. A key precedent is found in the large-scale SPICE project, which provides an existing research framework for citizen curation and cultural co-creation. Existing research within this benchmark proves that technical archival systems can move beyond mere documentation to actively safeguard marginalized identities. By integrating traditional Iranian and Italian motifs into public spaces to act as a form of social justice,

this thesis explicitly builds upon the co-creation and inclusion models validated by the SPICE project to foster intercultural dialogue and prevent identity erasure.

4. Immersive Heritage and the Dynamic Archive

The ambition to liberate flat, traditional graphic patterns from passive, 2D museum databases and transform them into immersive, 3D architectural spaces directly mirrors the cutting-edge workflows of Project CHANGES. Existing research under this massive, interdisciplinary benchmark has already proven the efficacy of using high-fidelity digital twins, structured light scanning, and photogrammetry to preserve and visually re-engineer ephemeral cultural exhibitions and historical environments. This thesis builds explicitly upon the technical foundation laid by Project CHANGES, taking it a step further by directly analyzing the human side of the interaction—measuring how contemporary public audiences respond to these digital interventions to turn a static historical record into a living public experience.

The current landscape of digital cultural preservation is defined by a significant disconnect between high-fidelity data collection and the functional preservation of cultural meaning. Despite advancements in archival technology, three primary challenges remain unresolved:

Current computational models excel at capturing the "aesthetic surface" of heritage—the colors, shapes, and textures—but fail to encode the underlying traditional semiotic structures. These structures represent the internal logic and "visual grammar" of a motif (for example, the mathematical symmetry of geometric tiling or the narrative hierarchy of textile patterns). Without a framework to digitize this symbolic logic, assets remain static data points rather than dynamic systems of cultural communication.

A critical hurdle in the digital humanities is the inability to effectively synthesize qualitative character dynamics with quantitative emotional trajectories. As critics of the "spatial turn" in digital mapping argue, most existing visualizations prioritize raw geospatial data over the emotional, phenomenological, and historical weight of the narrative[38]. This limitation makes it difficult to create computational models that can bridge the gap between the profound meaning of ancient motifs and the interpretative needs of modern scholarly engagement.

[38] Bodenhamer, Corrigan, & Harris, 2010, pp. 24–28

By failing to quantify or visualize the lived, emotional experience of a space, standard digital documentation reduces rich cultural landscapes to sterile coordinates[39]. Consequently, this research addresses this specific limitation by utilizing the Digital Twin framework not merely as a tool for geometric and spatial recording, but as an immersive environment capable of encoding and projecting the qualitative, narrative layers of heritage patterns back into contemporary [40]architectures[41].

There is a fundamental tension between the fragmented, entertainment-oriented digital consumption habits of contemporary audiences and the sustained interaction required by complex historical narratives. Current state-of-the-art tools often default to over-simplification to ensure accessibility, which risks eroding the authenticity of the cultural memory. A prominent example of this limitation is found in commercial virtual reality heritage applications, such as the initial digital reconstructions of Rome on Google Earth or simplified historical gamification in popular media; these platforms frequently isolate structural facades from their socio-political contexts, reducing intricate architectural history to passive, aestheticized backgrounds. The challenge lies in developing unified computational visualizations that provide the immediacy of modern digital interfaces without sacrificing the historical complexity of the source material.

Despite these challenges, the rise of increasingly accessible digitization methods has created a pivotal opportunity to reintegrate both intangible and tangible cultural heritage into contemporary life. In this context, intangible heritage refers to the traditional knowledge systems, spiritual values, and mathematical logic—such as the rules of symmetry or narrative sequences—that inform the creation of visual artifacts.[42]

Traditional motifs must be understood as more than mere decorative elements; they function as significant carriers of identity and artistic expression. Their visual and symbolic complexity conveys historical narratives and belief systems, operating as embedded semiotic structures that elicit deep emotional and cognitive connections to place and heritage. This research specifically analyzes the following traditional motifs, selected for their diverse cultural origins and historical depth:

These motifs were selected because they represent a global spectrum of visual languages—ranging from mathematical abstraction to botanical realism—that are currently endangered by fragmented digital consumption. By digitizing these specific systems through digital twin technology, the

[39] Jessop, 2008, pp. 40–43
[40] Daquino, Pasqual and Tomasi 2020, p. 10-17
[41] Niu, 2025, pp. 18–20; Manovich, 2001, pp. 218–222
[42] Rezazadeh (2024), pp. 112-140, Niu (2025), pp. 12-15

research ensures that the "intangible" logic of these patterns is preserved and adapted for contemporary spatial environments.

The selection of motifs for this study covers a diverse range of cultural traditions, starting with Girih from the Safavid Era in Iran, which consists of interlaced geometric patterns based on precise mathematical rules that represent spiritual and philosophical principles through star and polygon configurations[43]. In contrast to this rigid geometry, the New Zealand Māori Koru provides a fluid, spiral motif based on the unfurling fern frond, functioning as a powerful symbol of new life, growth, and the continuity of time and lineage[44]. Representing a completely different spatial grammar, Australian Aboriginal Dot Painting uses an abstract yet deeply symbolic language to map ancestral stories, sacred waterholes, and geographical journeys across physical terrain[45].

Moving to European folk traditions, Polish Wycinanki and Parzenica rely on intricate floral paper cut-outs and heart-shaped decorative knots found in regional costumes and home décor to signify local identity and artisanal craftsmanship[46]. Similarly, nineteenth-century Swiss St. Gallen Lace brings a tradition of high-fashion textile artistry defined by intricate, ornamental floral work[47]. This textile aesthetic is complemented by seventeenth-century Dutch Delftware, which features iconic blue-and-white ceramic patterns depicting pastoral or biblical scenes deeply rooted in the Dutch Golden Age[48]. Finally, Italian Bargello and Majolica bridge the gap between textile and ceramic artistry, utilizing flame-stitch embroidery from Florence and vibrant glazed ceramic designs from Sicily to embody classic Mediterranean botanical and geometric aesthetics[49].

Participation with these patterns facilitates essential processes of recognition, reflection, and intergenerational continuity. When these motifs are removed from their historical silos and integrated into modern digital frameworks, they transition from static artifacts into living conduits of cultural information.[50]

The core of this research proposes a transition from passive archiving to active, technological reinterpretation. By leveraging Digital Twin technologies and three-dimensional modeling, this study

[43] Necipoğlu, 1995, p. 42-57
[44] Mead, 2016, p. 26
[45] Morphy, 1998, p. 25
[46] Jackowski, 2002, p. 68-73
[47] Tanner, 2012, p. 38
[48] Van Dam, 2004, p. 2
[49] Fiocco & Gherardi, 2002; Williams, 2015, p. 4-5
[50] Galani, S., & Vosinakis, S. (2024), p. 13-16

seeks to generate innovative reinterpretations of traditional patterns that maintain their historical integrity while adapting to contemporary design requirements[51].

1.1.Literature Review

This research builds upon a well-established body of literature that addresses the intersection of cognitive science, media studies, and cultural preservation. Previous scholarship has extensively documented the shift in information processing within digital environments, noting that the rise of fragmented content has created a significant barrier to traditional deep engagement with long-form historical and cultural narratives. This body of work provides the necessary evidence for the "attention gap" that this thesis seeks to bridge through visual and technological intervention.

Furthermore, the methodology of this study aligns with existing research into the semiotic power of visual motifs, which identifies these patterns as functional conduits of identity rather than mere aesthetic ornaments. Existing academic frameworks for "distant reading" and computational analysis provide the tools for quantifying what was once considered purely subjective artistic data. By synthesizing these established theories, this research moves beyond simple archiving, drawing on contemporary studies that advocate for the use of immersive technologies to ensure that cultural memory remains a living, functional asset in a digital-first society.

The following literature forms the theoretical and methodological foundation for the design approaches adopted in this study and supports its continued development.

The analytical frameworks and visual taxonomies presented herein are synthesized from a rigorous review of the referenced literature, which served as the foundational basis for shaping the research models and figures.

[51] Giacomini et al. 2025, p. 70

List of 60 Literature:

1*Yu and Zheng (2025), [52]representing Shangluo University and Shanxi Datong University, China, investigate the integration of traditional pattern elements into modern packaging design to enhance visual appeal and consumer engagement. Their research quantifies that such integrations improve visual effects by 10% to 20%, utilizing 3D mesh algorithms and eye-tracking technology to measure the correlation between heritage motifs and heightened consumer satisfaction.

2* Wang, Sheng, and Ghani (2025) [53]examine the digital collection, digitization, and reconstruction of traditional motifs through the application of Generative Adversarial Networks (GANs). Their research demonstrates how these computational frameworks effectively facilitate innovative design, providing a robust model for the symbiosis of cultural diversity and modern technological applications.

3*Yuan (2025) [54]examines strategic methodologies for integrating traditional Chinese auspicious animal patterns into modern commercial poster illustrations. This research highlights how the application of these heritage motifs enhances the cultural value and market competitiveness of creative industries within contemporary commercial contexts.

4*Meng, Li, Shu, Chen, Han, and He (2025) [55]propose a GAN-driven framework for the digital preservation and regeneration of traditional Yi ethnic patterns within a structured database. Their research demonstrates how these computational models can revitalize marginalized designs for integration into textiles, architecture, and contemporary digital media.

5*Gao, Ariffin, Hussein, and Wang (2024) [56]present a systematic literature review focused on the conservation of traditional patterns within Chinese traditional villages. Their study proposes an integrated framework that combines harmonized policy-making, active public participation, and adaptive utilization strategies to ensure the sustainable preservation and contemporary development of rural cultural landscapes.

6*Asriana and Khidmat (2024) [57]decode the spatial layout patterns of Indonesian urban kampung settlements, identifying axially configured and integrated designs centered around spacious halls. Their findings reveal that these traditional housing structures, utilized by both indigenous and non-

[52] Zhao, Y., & Zheng, R. (2025), p.3
[53] Wang, Sheng and Ghani, (2025), p.44-48
[54] Yuan, M. (2025), p. 76
[55] Meng, K., Li, H., Shu, Y., Chen, M., Han, X., & He, L. (2025), p. 12
[56] Gao, L., Ariffin, N. F. M., Hussein, M. K. B., & Wang, B. (2024), p. 30
[57] Asriana, N., & Khidmat, R. P. (2024), p. 74-80

indigenous dwellers, naturally incorporate social distancing principles, providing a critical spatial resource for the preservation of traditional vernacular architecture.

7* Dong (2025) [58] investigates the "ecological code" of landscape cities by analyzing traditional Feng Shui patterns in relation to modern sustainable spatial designs. The research specifically evaluates the mechanical properties of architectural materials, finding that the integration of metakaolin, fly ash, and silica fume significantly reduces mortar drying shrinkage and enhances compressive strength by 20–40% and flexural strength by 20–30%.

8* Zhao, Lombardi, Yang, and Lui (2025) [59] introduce a parametric design and digital fabrication workflow for reinterpreting traditional Chinese window lattice patterns in contemporary architecture. Their research utilizes daylighting performance as a primary selection criterion, establishing a seamless file-to-fabrication methodology that assists designers in applying heritage motifs to modern structural requirements.

9* Tian, Liu, and Lu (2024) [60] utilize grounded theory to analyze Pang Xunqin's "Chinese Decorative Pattern Collection," exploring the fusion of traditional motifs with modern decorative art. Their research establishes a dynamic model for the contemporary evolution of these patterns, emphasizing how such integrations enhance cultural identity and facilitate global dissemination within the modern aesthetic landscape.

10* Zaharieva-Stoyanova (2024) [61] presents a specialized CAD framework for the digital preservation and presentation of traditional Bulgarian embroidery. The research introduces cross-stitch software designed to digitize ethnographic exhibits, utilizing a methodology that outlines specific stitch types and groups identical pattern sets to facilitate modern digital representation and design.

11* Wu and Kyungsun (2022) [62] present an AI-driven system utilizing Generative Adversarial Networks (GANs) coupled with aesthetic evaluation technology for the autonomous production of high-quality traditional Chinese decorative patterns. Their framework focuses on optimizing design efficiency and versatility, ensuring that automatically generated motifs meet rigorous aesthetic standards for contemporary application.

12* Shin and Westland (2017) develop a digital design tool derived from the computational rules of traditional Korean bojagi patterns. Their research translates this historical construction logic into a

[58] Dong, B. (2025), p. 21-25
[59] Zhao, J., Lombardi, D., Yang, S., & Lui, J. (2025), p. 6
[60] Tian, X., Liu, X., & Lu, C. (2024), p. 14-16
[61] Zaharieva-Stoyanova, E. (2024), p. 85-88
[62] Wu, Y., & Kyungsun, K. (2022), p. 10

digital framework, facilitating the modern application of traditional motifs within fashion, interior design, marketing, and educational contexts.

13* Habib and Alam (2024) [63] perform a comparative analysis between 3D virtual pattern-making and traditional manual methods within the garment industry. Their study demonstrates how 3D fashion design software optimizes efficiency and reduces environmental impact, providing an intuitive, skill-accessible framework for professionals to create virtual garments while minimizing physical prototyping costs.

14* Stones and Cassidy (2006) [64] Conduct a comparative study of synthesis strategies used by novice graphic designers when employing digital versus traditional tools. Their findings indicate that paper-based sketching produces more diverse and fluent design solutions during early-stage thinking, highlighting the necessity of integrated methodologies that combine traditional tactile sketching with digital design to achieve balanced creativity.

15* Wang and Pan (2023) [65] analyze the integration of traditional Chinese culture into modern interior design as a strategy to counteract aesthetic homogenization. Their research emphasizes that embedding national heritage within contemporary spaces enriches cultural identity and creates functionally meaningful environments that bridge the gap between historical legacy and modern utility.

16* Ali, Al-Hashimi, and Al-Samman (2018) [66] evaluate the sustainability of the traditional urban form in the Old City of Sana'a compared to modern developments. Utilizing GIS, ECOTECT, and Space Syntax analysis, their research demonstrates that traditional layouts outperform modern designs in walkability, connectivity, and solar energy efficiency, advocating for the integration of historical urban density principles into contemporary sustainable design.

17* Wesnina, Prabawati, and Noerharyono (2025) [67] analyze the evolution of Indonesian batik motifs through the integration of traditional craftsmanship and contemporary digital design. Their research proposes a sustainable, collaborative framework that utilizes digital techniques to ensure modern relevance and artistic innovation while strictly preserving the cultural integrity and symbolic heritage of the original batik forms.

[63] Habib, A., & Alam, S. (2024), p. 8
[64] Stones, C., & Cassidy, T. (2006), p. 15-23
[65] Wang, L., & Pan, J. (2023), p. 43
[66] Ali, H. H., Al-Hashimi, I. A., & Al-Samman, F. (2018), p. 68-77
[67] Wesnina, W., Prabawati, M., & Noerharyono, M. (2025), p. 34-41

18* Shuaib and Enoch (2014) [68] investigate the integration of traditional Malay design elements into contemporary architecture, focusing on the rich aesthetic and philosophical heritage of Kelantan and Terengganu. Their research demonstrates how incorporating these indigenous motifs and structural principles serves as a sustainable innovation strategy to preserve national heritage and strengthen local identity within modern built environments.

19* Sarhangi (2016) [69] explores the enduring influence of traditional Persian mosaic design and architectural elements on modern aesthetics. Through the lens of geometric analysis and digital reconstruction, the research demonstrates how these historically rooted patterns continue to inspire contemporary design, highlighting the value of interdisciplinary approaches that connect mathematical principles with cultural heritage.

20* Yang, Wang, and Zhu (2011) [70] perform a comparative study between low-carbon interior design and traditional design methods. Their research concludes that while traditional methods provide a historical foundation, low-carbon design—leveraging advanced technologies and sustainable materials—offers superior environmental performance and remains essential for the future of sustainable architectural development.

21* Namer and Tornielli (2025) [71] Detail the implementation of the Fincantieri Digital Twin model, which synchronizes shipyard construction and production processes with a sophisticated suite of AI, robotics, IoT, and real-time data analytics. Their research underscores how this integrated digital framework enhances automation and operational control, facilitating data-driven decision-making across the entire naval supply chain.

22* Matta (2024) [72] provides a foundational overview of Digital Twins as high-fidelity virtual representations of physical objects. The research highlights their critical role in system analysis, optimization, and real-time decision-making, outlining the essential characteristics and modeling requirements necessary to maintain a synchronized link between a real-world entity and its digital counterpart.

23* Amoore (2025) [73] shifts the discourse on Digital Twins from technical feasibility to political agency, arguing that these models are not mere "copies" but active political technologies shaped by deep learning and unstructured data. The research identifies three core logics—intervention,

[68] Shuaib, A. A., & Enoch, O. F. (2014), p. 110-112
[69] Sarhangi, R. (2016), p. 9-10
[70] Yang, Y., Wang, F., & Zhu, X. (2011), p. 37-39
[71] Namer, T. P., & Tornielli, M. (2025), p. 2-5
[72] Matta, A. (2024, December 15–18), p. 54
[73] Amoore, L. (2025, August 2), p. 4

prediction, and action—that redefine how humans, objects, and environments are governed across industrial, medical, and military landscapes.

24* Hemamalini et al. (2025) [74] define the Digital Twin (or virtual twin) as a high-precision virtual representation of a physical system, designed to predict future behaviors following structural or operational modifications. Their research emphasizes the synergy between Digital Twins and blockchain technology to optimize manufacturing processes, ensuring data integrity and security while exploring diverse modeling and simulation techniques for industrial applications.

25* Wieme, Baer, and Hoebeke (2025) [75] address the critical lack of standardization in Digital Twin Networks (DTNs) by providing a comprehensive implementation guide. Their architectural framework focuses on the technical pillars of scalability, interoperability, and real-time communication. By outlining essential data modeling and security components, the research offers a strategic roadmap for deploying interconnected digital twins that can function cohesively across complex network environments.

26* Ravinder (2025) [76] explores the transformative impact of Digital Twin technology on the construction industry, framing it as a dynamic integration of physical assets with high-fidelity virtual models. The research demonstrates how real-time data streams—facilitated by AI, IoT, and cloud computing—enable stakeholders to monitor performance, predict structural issues, and resolve asset-related inefficiencies before they manifest in the physical world.

27* Shen, Wagg, Tipuric, and Bonney (2025) [77] propose a novel framework where digital twins function as "self-models" for intelligent structures. Utilizing an agent-based architecture to simulate a three-story building, the research integrates knowledge graphs and natural language processing. This allows the digital twin to not only mirror physical states but also interact with users through conversational queries, enabling dynamic task execution and sophisticated information management within the built environment.

28* Florido-Benítez (2025) [78] examines the application of Digital Twin (DT) technology within the framework of Smart Tourist Destinations (STDs). The research highlights how virtual replicas of tourism infrastructure enable more precise urban planning, enhanced security, and sustainable resource management. By utilizing real-time data analysis and predictive modeling, the study

[74] Hemamalini, U., Bharathi, A., Prasanth, A., Manjula, P., & Devi Sowndarya, K. K. (2025), p. 80
[75] Wieme, J., Baer, M., & Hoebeke, J. (2025), p. 37-39
[76] Ravinder, B. (2025), p. 53-55
[77] Shen, X., Wagg, D. J., Tipuric, M., & Bonney, M. S. (2025), p.3
[78] Florido-Benítez, L. (2025), p. 1-3

demonstrates that DTs can simultaneously elevate the tourist experience and improve the quality of life for local residents through optimized public services and infrastructure resilience.

29* Hasan and Crawford (2025) [79] Provide a comprehensive evaluation of the core components and cross-industry applications of Digital Twin (DT) technology. Their research highlights the transformative role of DTs in sectors such as manufacturing, healthcare, urban planning, and energy. By integrating enabling technologies—specifically machine learning for predictive insights, edge computing for localized data processing, and blockchain for secure data integrity—the authors outline a framework for building scalable and resilient digital ecosystems that bridge the gap between physical operations and virtual optimization.

30* Minerva (2024) [80] addresses the "Information Problem" inherent in Digital Twin (DT) implementation, framing the technology as a complex orchestration of sensing, data management, and AI. The research emphasizes that a functional DT requires both descriptive models (to mirror the system) and prescriptive models (to guide it). A key contribution is the concept of "synthetic sensing"—using AI to transform raw data into actionable insights—and the necessity of evolving cloud platforms to handle the specialized data transformation requirements of these advanced virtual replicas.

31* Pasupuleti (2025) [81] provides a holistic framework for the application of Digital Twin technology in the preservation of cultural heritage. The research focuses on the synergy between AI-powered digital twins, high-resolution 3D scanning, and IoT sensors to create high-fidelity virtual replicas of historical monuments and artifacts. By integrating blockchain-based digital archiving and real-time simulations, Pasupuleti demonstrates how these "living" models enable predictive conservation and immersive virtual tourism, while addressing the critical ethical and policy frameworks necessary to protect intangible cultural traditions from material degradation and global environmental threats.

32* Buzzoni, Burgio, Modena, and Simion (2016) [82] evaluate the efficacy of computer-assisted quantitative methods versus traditional qualitative stemmatics in textual analysis. Their study highlights a critical performance gap: while computational models are highly effective at grouping witnesses and identifying variant readings in "open recensions" (flexible textual transmissions), they struggle to define precise sub-groups within "closed recensions." The findings suggest that digital

[79] Hasan, S. K. K., & Crawford, C. W. (2025), p. 7
[80] Minerva, R. (2024), p. 90
[81] Pasupuleti, M. K. (2025), p. 76-77
[82] Buzzoni, M., Burgio, E., Modena, M., & Simion, S. (2016), p. 32

stemmatology is most reliable when applied to fluid traditions, necessitating a hybrid approach that maintains traditional philological oversight for rigid, hierarchical lineages.

33* Burgio, Buzzoni, and Simion (2024) [83] present the first comprehensive digital scholarly edition of Marco Polo's Devisement dou monde, launched as an open-access and open-source platform. By providing a synoptic presentation of 12 manuscript versions across 11 languages, the project utilizes digital architecture to manage textual mobility. The edition integrates a critical English translation, a specialized glossary, and interactive maps, demonstrating how digital platforms can transform static historical manuscripts into dynamic, accessible, and interdisciplinary research tools for global scholarship.

34* Bruno, Sabatino, and Tomasi (2025) [84] propose a formal modeling framework for tracing the evolution of fictional characters in detective fiction across two centuries. Leveraging Semantic Web technologies and Digital Humanities methodologies, the research develops a taxonomy to analyze narrative intertextuality and character traits. By mapping stylistic and cultural recursiveness, the study provides a structured approach to understanding how storytelling techniques are transformed and recycled within the genre, offering a computational lens on narrative recurrence.

35* Bruno, Bocchi, and Tomasi (2025) [85] investigate the intermedial complexities of Edoardo Sanguineti's combinatory novel, Il Giuoco dell'Oca, through the application of Semantic Web technologies. The study introduces the Multimedia Interrelation Ontology (MIrO), a specialized model designed to formalize intermedial, intratextual, and interpretative connections within nonlinear literary works. By employing computational strategies for text enrichment, the research demonstrates how ontologies can move beyond mere data storage to become tools for critical interpretation, deepening the reader's engagement with the multifaceted layers of contemporary literature.

36* Massari, Peroni, Tomasi, and Heibi (2025) [86] evaluate the technical frameworks required to manage provenance and track metadata changes within cultural heritage RDF (Resource Description Framework) datasets. The study examines the efficacy of W3C standards—including RDF Reification, n-ary relations, Named Graphs, and the emerging RDF-star—alongside specialized ontologies like PROV-O and the OpenCitations Data Model (OCDM). By identifying the most robust approaches for maintaining a reliable "audit trail" of cultural data, the research provides a critical foundation for ensuring the long-term integrity and transparency of digital humanities archives.

[83] Burgio, E., Buzzoni, M., & Simion, S. (2024), p. 12-19
[84] Bruno, E., Sabatino, L., & Tomasi, F. (2025), p. 64
[85] Bruno, E., Bocchi, M. F., & Tomasi, F. (2025, June), p. 20-22
[86] Massari, A., Peroni, S., Tomasi, F., & Heibi, I. (2025), p. 25-29

37* Giacomini et al. (2025) [87] examine the transformative impact of the Semantic Web on the GLAM (Galleries, Libraries, Archives, and Museums) sector, specifically addressing the challenges of content heterogeneity and varying levels of technical expertise among users. The research introduces CLEF 2.0, a native Linked Open Data (LOD) cataloging software designed to streamline the management of Italian digital cultural heritage. By integrating crowdsourcing and LOD principles, the platform provides a scalable solution for creating interconnected, interoperable cultural datasets, as demonstrated through diverse real-world case studies in the Italian landscape.

38* Bruno, Pasqual, and Tomasi (2024) [88] explore the combinatorial "narrative machine" of Italo Calvino's Il Castello dei Destini Incrociati using Semantic Web technologies. The research formalizes the complex relationships between tarot cards and their narrative roles by developing the ODI (Ontologia dei Destini Incrociati) and the BACODI Knowledge Base. These tools allow for a computational analysis of Calvino's literary structures, which are then visualized through MACODI, a web application that provides a multilayered, interactive view of the data. This project demonstrates how formal ontologies can bridge the gap between creative literary constraints and digital knowledge representation.

39* Balzani et al. (2023) [89] detail the methodology for preserving temporary exhibitions through high-fidelity digital twins as part of Project CHANGES. Using the exhibition "The Other Renaissance: Ulisse Aldrovandi and the Wonders of the World" as a pilot, the researchers employed a hybrid acquisition strategy combining structured light projection scanning and photogrammetry. The study outlines a comprehensive pipeline—acquisition, processing, optimization, and metadating—designed to ensure the final digital assets adhere to FAIR principles (Findability, Accessibility, Interoperability, and Reusability). This work demonstrates how open-source technologies and standardized metadata can transform ephemeral physical events into permanent, interactive virtual environments for both scholarly research and public engagement.

40* Sartini, Baroncini, van Erp, and Gangemi (2023) [90] introduce ICON, a formal ontology designed to model the complex layers of artistic interpretation. Grounded in Erwin Panofsky's tripartite theory of art history (pre-iconographical description, iconographical analysis, and iconological interpretation), the ontology provides a structured framework for capturing not just what an artwork depicts, but what it means symbolically and culturally. By integrating diverse ontologies from semiotic and symbolic domains, ICON enhances the Linked Open Data (LOD) ecosystem, allowing

[87] Giacomini, S., Daquino, M., Tomasi, F., & Fintoni, L. A. (2025), p. 70
[88] Bruno, E., Pasqual, V., & Tomasi, F. (2024). P. 47–69.
[89] Balzani, R., Barzaghi, S., Bitelli, G., Bonifazi, F., Bordignon, A., Cipriani, L., ... & Vittuari, L. (2023), p. 32
[90] Sartini, B., Baroncini, S., van Erp, M., & Gangemi, A. (2023) p. 1–28.

art historians and machines alike to navigate the deep, interpretative narratives behind cultural artifacts.

41* Daquino, Pasqual, Tomasi, and Vitali (2022) [91] address a fundamental tension in Digital Humanities: how to represent the "non-asserted" or subjective nature of artistic scholarship using RDF, which is traditionally designed for absolute, fact-based triples. The researchers propose a solution centered on "Conjectures"—a model that utilizes RDF Named Graphs to encapsulate claims without assigning them a definitive truth value. By categorizing statements into three states—undisputed, disputed, and settled—the framework allows scholars to record conflicting attributions (e.g., competing theories on an artwork's creator) and uncertain interpretations as first-class citizens in a knowledge graph. This approach ensures that the nuanced, often argumentative "audit trail" of art history is preserved rather than flattened into a single, potentially misleading "truth."

42* Daquino, Pasqual, and Tomasi (2020) [92] address the "Hermeneutic Problem" in Digital Humanities: the challenge of formally representing the process of interpretation itself rather than just the final data. The research introduces a portable data model based on Semantic Web technologies, designed to capture the cross-disciplinary analysis of archival and literary sources. By formalizing the interpretive path taken by a researcher—including the handling of contradictory or uncertain information—the model significantly improves the reproducibility and peer assessment of digital scholarship. Through three distinct Cultural Heritage scenarios, the authors demonstrate how a structured knowledge representation can bridge the gap between subjective human interpretation and machine-readable data.

43* Daquino, Mambelli, Peroni, and Vitali (2016) [93] detail the technical workflow of transforming the Zeri Photo Archive, one of Europe's most significant art history collections, into a Linked Open Data (LOD) ecosystem. To address the descriptive gaps in existing models, the researchers developed two specialized ontologies—the F Entry and OA Entry Ontologies—based on Italian national cataloging standards (Scheda F and Scheda OA). By mapping complex archival metadata to RDF, the project demonstrates how to preserve the high-granularity relationships between a photograph, the artwork it depicts, and the scholarly annotations attached to it. This work serves as a foundational case study for the challenges of balancing standardized interoperability with the specific, intricate requirements of cultural heritage documentation.

[91] Daquino, M., Pasqual, V., Tomasi, F., & Vitali, F. (2022, January), p. 3-9
[92] Daquino, M., Pasqual, V., & Tomasi, F. (2020), p. 30
[93] Daquino, M., Mambelli, F., Peroni, S., & Vitali, F. (2016), p. 1–21

44* Daquino and Tomasi (2016) [94] explore the intersection between Digital Humanities (DH) and Library and Information Science (LIS) through the lens of knowledge organization. The research identifies a shared foundational interest in data modeling and the formalization of knowledge via ontologies. However, it distinguishes their primary objectives: while LIS focuses on the long-term preservation and retrieval of information, DH prioritizes the interpretation and critical analysis of that data. By examining these overlapping methodologies, the authors demonstrate how formal ontologies serve as the bridge between the structured cataloging of the past and the dynamic, interpretive research environments of the future.

45* Daquino and Tomasi (2015) [95] introduce the Historical Context Ontology (HiCO), an OWL 2 DL model designed to formalize the context of cultural heritage objects. HiCO specifically addresses the challenge of making "authoritative statements" about an object's history—such as its creation, provenance, or previous ownership—shareable and machine-readable. By providing a structured framework for data extracted from full-text documents, the ontology enables the exchange and reuse of heterogeneous data across different digital repositories, ensuring that the "story" behind an artifact remains as interconnected and accessible as the artifact's physical data.

46* Barbera, Meschini, Morbidoni, and Tomasi (2012) [96] present the SemLib project, a framework designed to bridge the gap between traditional digital libraries and the collaborative, interconnected world of the Semantic Web. The research proposes a model for collaborative semantic annotation, allowing scholars and users from diverse backgrounds to enrich digital editions with structured metadata. By leveraging Linked Data technologies, the project simplifies the integration of annotation tools into existing digital architectures, transforming static electronic texts into dynamic, evolving knowledge bases. The authors emphasize a user-friendly front-end that democratizes the act of scholarly commentary, ensuring that the "interpretive layer" of a digital edition is as robust and interoperable as the primary source itself.

47* Fischer, Mantoan, and Tramelli (2024) [97] reflect on the evolution of magazén as a specialized open platform at the intersection of Digital and Public Humanities. The researchers argue that the "Digital" and the "Public" function as reciprocal mirrors in contemporary scholarship; digital tools enable broader public access, while public engagement drives the development of more intuitive and open digital methodologies. This editorial transition—moving from strictly thematic methodological

[94] Daquino, M., & Tomasi, F. (2016). P. 113–133.
[95] Daquino, M., & Tomasi, F. (2015, September). pp. 424-436
[96] Barbera, M., Meschini, F., Morbidoni, C., & Tomasi, F. (2012). P. 13–24.
[97] Fischer, F., Mantoan, D., & Tramelli, B. (2024), p. 75

volumes to a broader open-access platform—signals a maturing field where the focus shifts from the internal mechanics of digitization to the external, social impact of shared cultural knowledge.

48*Fischer, Mantoan, and Tramelli (2022) [98]define the concept of [re]construction as a core methodology within Digital and Public Humanities. The research frames [re]construction not merely as the physical or digital rebuilding of a lost object, but as a scholarly "soul-searching" process that involves interpreting, modeling, and making historical knowledge visible to the public. By synthesizing twelve diverse papers, the authors argue that these digital reconstructions serve as hypotheses of the past, requiring rigorous documentation and open access to remain valid scholarly enterprises. This work emphasizes that the process of modeling is just as critical as the final product, bridging the gap between raw data and cultural storytelling.

49*Fischer, Mantoan, and Tramelli (2021) [99]reflect on the "consolidation" phase of Digital and Public Humanities (DPH) after two decades of rapid evolution. The editorial notes that the field has moved beyond mere experimentation into a state of academic self-awareness and methodological maturity. However, it highlights a persistent tension: while the technical and scholarly frameworks for DPH are now robust and "consolidated," the institutional structures—such as tenure-track stability and long-term funding—have yet to fully catch up. This source serves as a critical institutional critique, reminding researchers that the success of a digital project (like a Digital Twin or a Linked Data Archive) depends not just on the code, but on the sustainable academic ecosystem surrounding it.

50*Fischer, Mantoan, and Tramelli (2020) [100]announce the inaugural issue of *magazén* and the launch of the Venice Centre for Digital and Public Humanities (VeDPH) at Ca' Foscari University. This milestone marks a commitment to "disciplinary fusion," where the traditional boundaries between computer science and the humanities are dissolved to create a collaborative space for scholars, artists, and programmers. The center's mission is to lead the digital transformation of cultural heritage, ensuring that emerging technologies are not just applied to the humanities but are shaped by humanistic inquiry. This source provides the institutional "birth certificate" for the very frameworks (like the *Devisement du monde* digital edition) I have previously cited.

[98] Fischer, F., Mantoan, D., & Tramelli, B. (2022) p. 159–168.
[99] Fischer, F., Mantoan, D., & Tramelli, B. (2021). P. 163–172.
[100] Fischer, F., Mantoan, D., & Tramelli, B. (2020). P. 5–12.

51* Renda et al. (2025) [101] introduce Ragù, a pilot project tackling the digitization and preservation of Italian culinary heritage through traditional cookbooks. These domestic texts are often left on the sidelines of formal scholarly archives, but the authors transform them into a structured digital collection using low-cost crowdsourcing. What makes this relevant is how it balances community-driven data enrichment with digital storytelling, creating an accessible platform that saves both the recipes and their surrounding cultural narratives. By leveraging public participation, it offers a highly scalable model for saving "intangible" or "vernacular" cultural heritage that would otherwise slip through the cracks of history.

52* Giacomini et al. (2025) [102] Evaluate the ongoing shift within the GLAM (Galleries, Libraries, Archives, and Museums) sector toward Linked Open Data (LOD) and crowdsourced knowledge production. The authors address the messy realities of the field namely, fragmented data, heterogeneous content, and the varying technical literacy of heritage professionals—by introducing CLEF 2.0. This platform acts as a "native" LOD cataloguing solution built specifically for the Italian cultural landscape, making it easier to spin up interoperable datasets connected to the global Semantic Web. By stripping away the usual complexities of RDF-based cataloguing, the authors offer a practical, scalable bridge between traditional archival workflows and modern, decentralized digital scholarship.

53* Daquino (2024) [103] delivers a much-needed longitudinal reflection on how Semantic Web technologies and Linked Open Data (LOD) have fundamentally changed photo archive management over the last twenty years. Grounding the analysis in the ZERI & LODe project as a primary case study, the paper maps out the real "added value" of this technical shift: finer data granularity, smoother cross-repository searching, and richer user engagement. Crucially, the study doesn't just praise the tech; it balances these wins against the steep learning curves faced by cataloguers adopting new ontologies and scholars trying to navigate complex data structures. It functions as a definitive roadmap of how photo archives transitioned from static image walls into interconnected nodes within a global knowledge graph.

54* This massive collaborative study by Daquino and an interdisciplinary team of 34 authors serves as a masterclass in building Digital Twins for temporary cultural events. Looking at "The Other Renaissance"—an exhibition dedicated to the naturalist Ulisse Aldrovandi as part of Project CHANGES—the team goes far beyond standard 3D modeling. They deploy a hybrid acquisition

[101] Renda, G., Manganelli, G., Fumini, M., & Daquino, M. (2025), p. 79-82
[102] Giacomini, S., Daquino, M., Tomasi, F., & Fintoni, L. A. (2025), p. 8-9
[103] Daquino, M. (2024) p. 1–25

pipeline that fuses structured light scanning and photogrammetry with a robust semantic infrastructure. By tying bibliographical data directly to the 3D assets, they ensure the physical exhibition's "digital afterlife" strictly follows FAIR principles, turning a fleeting physical event into a permanent, interoperable, and reusable scholarly resource.[104]

55*Renda, Daquino, and Presutti (2023) [105]introduce MELODY, a specialized web interface built to solve a persistent issue: transforming dense Linked Open Data (LOD) into actual narrative experiences. Pointing out that standard data visualization tools usually strip away the human element of storytelling, the authors combine Ontology Design with UX methodologies to let users author proper "data stories." MELODY allows scholars and curators to query SPARQL endpoints and cleanly package those results into web-ready, narrative-driven documents. It is a fantastic tool for bridging the gap between raw semantic data and public engagement, offering a structured yet flexible way to translate complex cultural heritage insights for a broader audience.

56*This extensive study by Daquino et al. (2022) [106]and a multidisciplinary team of 16 authors unpacks the paradigm shift of Citizen Curation within the SPICE project framework (Social Cohesion, Participation, and Inclusion through Cultural Engagement). The paper pushes past top-down professional cataloging to bake "citizen experiences"—the highly personal, emotional, and social reactions of the public—straight into cultural heritage archives. The authors highlight a core tension: while Linked Data is great for technically anchoring these diverse viewpoints to authoritative records, doing so forces us to completely rethink data management. It forces a confrontation with messy questions of privacy, intellectual property, and the clash between personal interpretation and institutional authority. This work is a vital bridge connecting technical Semantic Web architecture with the democratic aims of Public Humanities.

57*Daquino and Tomasi (2016) [107]tackle the intersections between Library and Information Science (LIS) and Digital Humanities (DH). The authors argue that while these fields are frequently siloed, they are deeply unified by the shared practice of Knowledge Organization. Focusing heavily on data modeling and ontologies, the research shows how LIS provides the structural discipline needed for long-term preservation, while DH leverages those exact structures to run complex, interpretative analyses. It gives me the perfect theoretical justification for using highly technical archival

[104] Balzani, R., Barzaghi, S., Bitelli, G., Bonifazi, F., Bordignon, A., Cipriani, L., ... & Daquino, M. (2023), p. 40-43
[105] Renda, G., Daquino, M., & Presutti, V. (2023, September). pp. 1-10
[106] Daquino, M., Daga, E., d'Aquin, M., Gangemi, A., Kuflik, T., Lieto, A., ... & Mulholland, P. (2022). P. 1-35.
[107] Daquino, M., & Tomasi, F. (2016). P. 113–133.

standards—like LOD and RDF—to carry out deep humanistic readings of cultural artifacts, whether dealing with Batik textiles or complex literary texts.

58* Delfino, Lenzerini, and Poggi (2025) [108] provide the formal mathematical foundation for querying complex Knowledge Graphs. While the rest of my sources focus primarily on how to construct ontologies, Poggi and her colleagues zoom in on the deep logical challenge of "query entailment"—making sure that when someone searches a semantic database (like my Batik or Marco Polo archives), the system can logically infer correct answers even when dealing with incomplete data. This is an essential anchor for the "Technical Rigor" section of my thesis, ensuring the backend logic of these digital repositories is theoretically sound.

59* Ciracì (2025) [109] offers a vital strategic vision for where the field needs to go next, arguing that we need to move away from isolated, "boutique" digital projects and head toward a massive, interconnected Open Science Cloud. He advocates for a "dynamic research observatory" capable of tracking cultural heritage data in real time. This source fits perfectly into my "Sustainability and Future Trends" chapter, as it builds the case for why my Digital Twin research cannot exist in a vacuum; it needs to be integrated into a larger, cloud-based infrastructure to stay accessible and relevant over the long term.

60* Catarci (2025) [110] applies structural narrative theory (leaning on Propp and Freytag) to run an audit on AI-generated content, exposing how Large Language Models (LLMs) regularly replicate deeply ingrained gender biases when spinning narratives. For my thesis, this work injects a crucial ethical and sociological safeguard. If I end up using AI to generate contextual narratives for my digital artifacts (perhaps feeding into tools like MELODY), Catarci's methodology gives me the analytical framework to ensure those stories are fair, inclusive, and academically responsible.

1) The literature review employs a combination of scoping and narrative approaches, with a systematic literature review planned as a subsequent phase.

[108] Delfino, R. M., Lenzerini, M., & Poggi, A. (2025), p. 17-19
[109] Ciracì, F. (2025). P. 419–439.
[110] Catarci, T. (2025), p. 5-9

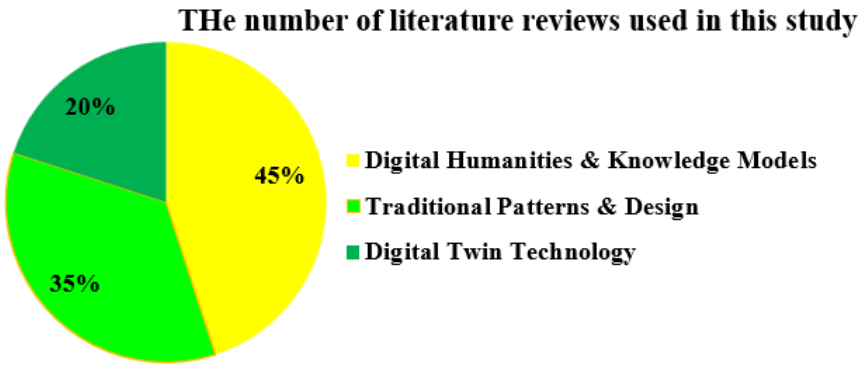


Figure 1: First Literature Review Data

The majority of studies concentrate on Digital Humanities and Knowledge Modeling, highlighting a strong emphasis on organizing, linking, and structuring cultural data. Traditional pattern design represents a secondary focus, reflecting ongoing efforts to preserve and modernize cultural motifs. Research on Digital Twins is comparatively smaller but expanding, indicating an emerging area of interest with significant growth potential.

Analyzing the general research field data from the first literature review reveals how the scholarly landscape is distributed across three foundational pillars.

The most prominent domain, accounting for 45% of the surveyed literature, centers on Digital Humanities and Knowledge Models. This expansive field leverages computational frameworks to systematically manage, analyze, and enrich humanistic data across a spectrum that spans textual analysis, digital editions, and formal knowledge organization systems. Within this track, fluid textual traditions and multi-lingual digital editions are examined by Buzzoni et al. (2016) [31] and Burgio et al. (2024) [32]. Literary narrative structures and semantic character tracking are explored using specialized taxonomies and ontologies by Bruno, Sabatino, and Tomasi (2025) [33] as well as Bruno, Bocchi, and Tomasi (2025) [34], while metadata provenance and native Linked Open Data (LOD) cataloging standards are evaluated by Massari et al. (2025) [35] and Giacomini et al. (2025) [36]. Computational breakdowns of complex literary constraints are addressed by Bruno, Pasqual, and Tomasi (2024) [37], while formal ontologies capturing art historical interpretations or handling scholarly uncertainty and conflicting attributions through RDF Named Graphs are advanced by Sartini et al. (2023) [39] and Daquino et al. (2022) [40].

To make cross-disciplinary archival pathways more reproducible, Daquino, Pasqual, and Tomasi (2020) [41] formalize the human interpretive process itself, which pairs with the technical data migrations seen in the Zeri Photo Archive LOD transformation by Daquino, Mambelli, Peroni, and Vitali (2016) [42]. The theoretical and practical integration of library science preservation with digital humanities interpretation is bridged by Daquino and Tomasi (2016) [43], while shareable object

provenance claims and collaborative semantic annotation tools are championed by Daquino and Tomasi (2015) [44] and Barbera et al. (2012) [45]. Cultural knowledge dynamics and public-facing digital reconstructions as rigorous scholarly hypotheses are detailed by Fischer, Mantoan, and Tramelli in their 2024 [46] and 2022 [47] works, which build upon their previous institutional critiques regarding funding sustainability in 2021 [48] and their celebration of disciplinary fusion at the Venice Centre for Digital and Public Humanities in 2020 [49]. Community-driven archiving for vernacular culinary heritage and decentralized shifts toward collaborative LOD production in the GLAM sector are examined by Renda, Manganelli, Fumini, and Daquino (2025) [50] and Giacomini, Daquino, Tomasi, and Fintoni (2025) [51]. Longitudinal changes in photo archive accessibility are outlined by Daquino (2024) [52], matching the curation needs met by semantic narrative UX tools like MELODY from Renda, Daquino, and Presutti (2023) [54] and the citizen curation co-creation models of Daquino et al. (2022) [55]. Finally, strict mathematical logic for query entailment over incomplete graph data by Delfino, Lenzerini, and Poggi (2025) [58], the call for interconnected Open Science Cloud infrastructures by Ciracì (2025) [59], and structural narrative audits to mitigate algorithmic bias in AI systems by Catarci (2025) [60] anchor the highly technical and ethical frontiers of this domain.

Representing 35% of the research, the second thread turns toward Traditional Patterns and Design. This discipline focuses heavily on historical motifs, traditional regional aesthetics, and manual crafting methodologies to see how they can be preserved, decoded, or adapted for modern visual culture. Integrating these historic motif elements into modern product packaging to boost consumer connection is tested by Yu and Zheng (2025) [1], while the digital collection, reconstruction, and generation of traditional motifs via Generative Adversarial Networks (GANs) are explored by Wang, Sheng, and Ghani (2025) [2]. Strategic choices for weaving auspicious animal motifs into commercial illustrations are analyzed by Yuan (2025) [3], while a machine-learning framework to rescue marginalized ethnic patterns is proposed by Meng et al. (2025) [4]. Pattern conservation balance within traditional villages is reviewed by Gao et al. (2024) [5], complementing the spatial layout and vernacular design decodings of urban settlements or Feng Shui ecological codes presented by Asriana and Khidmat (2024) [6] and Dong (2025) [7].

Reinterpreting traditional window lattices through parametric, fabrication-ready digital workflows is introduced by Zhao et al. (2025) [8], while historical collections are analyzed using grounded theory to inspire global identity by Tian, Liu, and Lu (2024) [9]. Specialized CAD frameworks to digitize traditional cross-stitch embroidery are designed by Zaharieva-Stoyanova (2024) [10], which pairs conceptually with the autonomous, GAN-driven pattern generation and aesthetic evaluation tools of Wu and Kyungsun (2022) [11]. The mathematical construction rules of historical bojagi patterns are

successfully translated into digital design software by Shin and Westland (2017) [12], while the environmental and practical choices of 3D virtual garment prototyping versus manual methods are weighed by Habib and Alam (2024) [13]. Novice design thinking across tactile and digital tools is studied by Stones and Cassidy (2006) [14], which runs parallel to the efforts of Wang and Pan (2023) [14] to embed regional cultural heritage into interior environments to combat aesthetic homogenization. Urban layout efficiencies of dense historic forms are demonstrated through space syntax by Ali, Al-Hashimi, and Al-Samman (2018) [15], while evolving traditional craftsmanship through collaborative digital batik workflows is mapped by Wesnina, Prabawati, and Noerharyono (2025) [16]. Lastly, incorporating indigenous design elements into contemporary architecture to bolster regional identity is investigated by Shuaib and Enoch (2014) [17], matching the geometric and mathematical analyses of traditional Persian mosaic designs by Sarhangi (2016) [18] and the low-carbon interior performance benefits of blending historical design foundations with advanced green materials by Yang, Wang, and Zhu (2011) [19].

The remaining 20% of the corpus is occupied by Digital Twin Technology, which investigates high-fidelity virtual replicas of physical entities by mapping the systems, network protocols, and sensory layers required to keep real-world objects and their digital counterparts synchronized. Industrial deployments, such as the Fincantieri shipyard supply chain twin, are detailed by Namer and Tornielli (2025) [20], while baseline real-time modeling and synchronization demands are provided by Matta (2024) [21]. The conversation is shifted to the political and governing agency of deep-learning twins by Amoore (2025) [22], while pairing virtual representations with blockchain architecture to secure manufacturing data integrity is executed by Hemamalini et al. (2025) [23]. Network communication bottlenecks and scalable, interoperable twin network roadmaps are designed by Wieme, Baer, and Hoebeke (2025) [24], while combining IoT streams, AI, and cloud computing for predictive construction management is evaluated by Ravinder (2025) [25]. Conversational building twins that allow natural language interactions with physical structures are implemented by Shen et al. (2025) [26], while virtual infrastructure replicas for sustainable tourist destinations are leveraged by Florido-Benítez (2025) [27]. Cross-industry applications tying together edge computing, machine learning, and blockchain are outlined by Hasan and Crawford (2025) [28], whereas Minerva (2024) [29] tackles the data-rich "Information Problem" by introducing AI-driven synthetic sensing. Predictive conservation of historical monuments using high-resolution 3D scanning and IoT sensor networks is built by Pasupuleti (2025) [30], while pipelines to transform ephemeral physical exhibitions into permanent interactive virtual environments or FAIR-compliant semantic digital twins of historical collections are realized by Balzani et al. (2023) [38] and Daquino et al. (2023) [53].

2) Semantic Web technologies (RDF, LOD, ontologies) dominate, meaning data structuring and interoperability are central to current research. AI/GANs and Digital Twin systems appear frequently, showing a shift toward automation, prediction, and intelligent modeling. 3D scanning and CAD tools support the preservation and recreation of cultural heritage.

In simple words, they help computers understand things *and how they are connected*, just like a smart, structured map of knowledge.

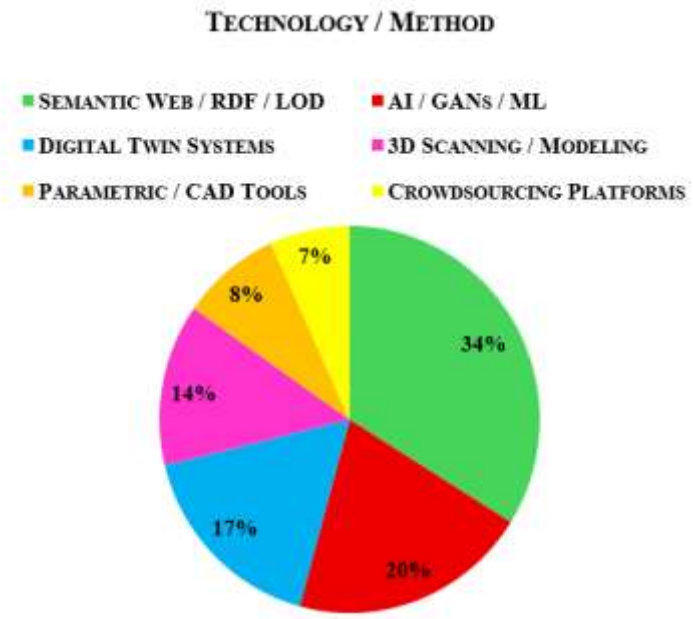


Figure 2: Second Literature Review Data

***RDF** → stores data in small "triples" like "Object – hasCreator – Person".

***LOD (Linked Open Data)** → connects datasets (e.g., museum records linked to Wikidata).

***Ontologies** → define concepts like "Artist," "Artwork," "Location," and how they relate.

Analyzing the technological and methodological approaches across the corpus reveals a diverse toolkit, with the Semantic Web, Resource Description Framework (RDF), and Linked Open Data (LOD) emerging as the most dominant paradigm at 34% of the literature. This substantial methodology—found in literatures [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [51], [52], [53], [54], [55], [57], and [58]—focuses on utilizing formal graph structures, custom domain ontologies, and SPARQL endpoints. By relying on interconnected open data, these projects are able to successfully map highly complex, subjective humanistic knowledge into machine-readable formats.

Artificial intelligence, Generative Adversarial Networks (GANs), and machine learning form the second-largest technical category, representing 20% of the reviewed studies. This computational

track, which spans literatures [2], [4], [11], [20], [22], [25], [26], [28], [29], [30], [31], and [60], places its focus on harnessing generative neural networks for visual pattern restoration. Beyond graphic recreation, these works lean heavily on deep learning predictive layers and automated bias auditing to maintain ethical and structural oversight.

Digital twin systems account for another 17% of the methodology focus, bringing a highly dynamic framework to the literature. Utilized in the literature [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [38], [53], and [59], this approach centers on constructing real-time cyber-physical feedback loops. Researchers working in this space focus on establishing scalable network configurations and interactive virtual environment simulations that stay continuously synchronized with their real-world counterparts.

Capturing physical reality directly, 3D scanning and modeling techniques make up 14% of the methodological landscape. Grounded in the literature [1], [13], [31], [38], and [53], this practical track focuses on digitizing tangible cultural assets through structured light scanning and photogrammetry. Once the physical data is captured, these workflows utilize mesh processing and virtual fabric prototyping to translate historical artifacts into precise digital models.

Parametric and CAD tools represent 8% of the technical applications within the corpus. Found in the literature [8], [10], [12], and [13], this category focuses on the rule-based generation of form. It achieves this by coding strict algorithmic design rules, executing complex vector-space matrix manipulations, developing customized stitch-generation software, and writing direct file-to-fabrication scripts for contemporary production.

Finally, making up the remaining 7% of the data are crowdsourcing platforms. Driven by the literature [36], [50], and [51], this methodology shifts the technical burden away from isolated institutions by enabling public-driven metadata enrichment. This approach focuses on fostering community archiving and deploying open, collaborative cataloging solutions that democratize how cultural data is gathered and preserved.

3) Most studies focus on the digital preservation of cultural heritage, reflecting a global commitment to safeguarding traditions. Digital tools and AI also foster design innovation, while improved accessibility, public engagement, and sustainability highlight the broader educational and resource-management benefits of digital transformation.

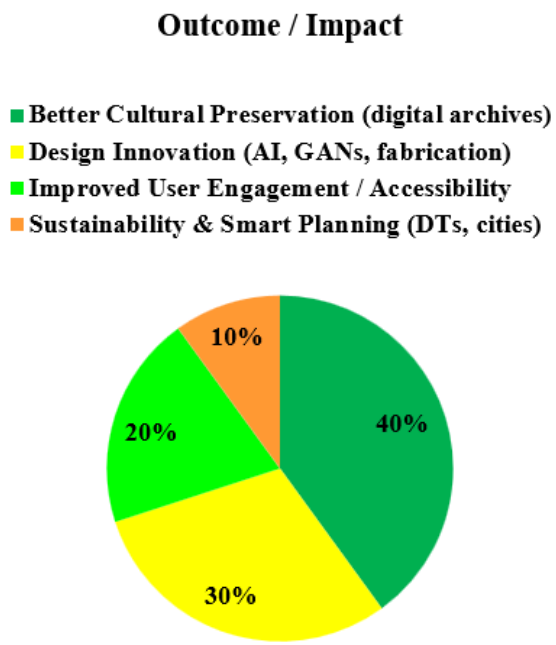


Figure 3: Third Literature Review Data

Looking at the third literature review data regarding outcome and impact, the practical applications of the research unfold across four major societal and technical dimensions.

The most prominent impact area, claiming 40% of the research focus, points directly toward better cultural preservation and the creation of digital archives. This heavy-hitting collection—which draws on literatures [4], [5], [10], [31], [32], [35], [36], [42], [46], [48], [49], [50], [51], [52], [53], [57], and [58] dedicates its outcomes to securing permanent, open-access repositories. The real-world impact here lies in safeguarding highly threatened material artifacts, mapping convoluted digital text lineages, and capturing fragile community records before they are lost to time.

Following closely behind, design innovation driven by AI, GANs, and digital fabrication represents 30% of the corpus impact. Supported by the literature [2], [8], [11], [12], [13], [14], [17], [20], [23], [24], and [29], this branch of the literature focuses on shaking up the studio and the factory floor. By streamlining and enhancing creative commercial workflows, these studies successfully minimize physical prototyping overhead and optimize complex manufacturing design pipelines through smart automation and predictive modeling.

Another 20% of the literature prioritizes improved user engagement and accessibility. This forward-facing group made up of literature [1], [9], [34], [37], [38], [39], [45], [47], [54], [55], and [60] seeks to completely transform flat, uninspiring datasets into deeply immersive public exhibits. Beyond just making things interactive, these works use advanced methods like biometric tracking to scientifically validate design appeal while building ethical narrative frameworks that respect the diverse audiences interacting with the heritage.

Finally, rounding out the final 10% of the review data is the focus on sustainability and smart planning, specifically through digital twins and urban analysis. Anchored by literatures [6], [7], [14], [15], [16], [18], [19], [21], [25], [26], [27], [28], and [59], this sector applies humanistic data to the built environment. Its tangible impacts include developing innovative green material solutions, restructuring cities to improve urban layout walkability, and deploying real-time predictive infrastructure monitoring to make modern spaces more sustainable and responsive.

4) The bar chart illustrates the distribution of four main thematic areas across sixteen publications in the reviewed literature, indicating that traditional patterns constitute the most frequently addressed topic in the analyzed titles.

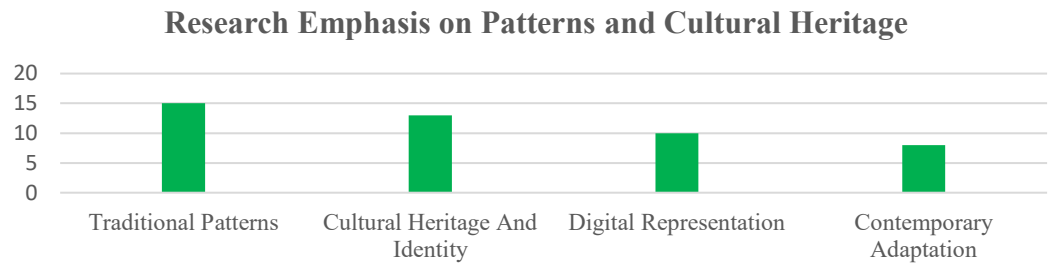


Figure 4: Fourth Literature Review Data

When evaluating the research emphasis on patterns and cultural heritage based on the fourth literature review data, the academic focus naturally divides into four distinct thematic pillars.

The first core pillar dedicates itself directly to traditional patterns. This specific cluster, represented by the literature [1], [2], [4], [8], [10], [11], [12], [16], and [18], focuses its energy on breaking down the structural calculus, geometric repetition rules, and technical craft parameters of historical ornamentation. Rather than looking at these designs purely as passive decorations, these studies analyze the underlying math and systems that govern their creation.

Shifting the focus toward a more human-centric perspective, the second pillar investigates cultural heritage and identity. Comprising literatures [3], [5], [9], [14], [17], [31], [38], [50], [53], [55], and [57], this segment emphasizes safeguarding regional vernacular identities from commercial aesthetic leveling. Its main goal is to give a long-term, stable structure to intangible community memory, ensuring that local histories are not erased by global design trends.

The third area of research transitions into the virtual realm with digital representation. This methodological track spanning literatures [32], [33], [34], [35], [36], [37], [39], [40], [41], [42], [43], [44], [51], [52], [58], and [60] places its emphasis on mapping textual flux and handling qualitative

scholarly debate directly within mathematical data structures. It also plays a crucial role in auditing narrative algorithms to ensure that computerized interpretations of history remain rigorous and fair.
Finally, the fourth pillar explores contemporary adaptation, bridging historical legacy with modern utility. Grounded in literatures [1], [3], [6], [7], [13], [14], [15], [19], [45], [46], [47], [54], and [59], this research actively tests historical motifs within current commercial markets. These works focus on adapting ancestral spacing and architectural layout rules to fit modern, functional spaces while also pioneering the technical pipelines needed for streaming live cultural data.

5) The chart illustrates the distribution of publications addressing the related themes of cultural identity revival and preservation. The results reveal that preservation is more prominently represented and more frequently emphasized than revival in the current scholarly literature.

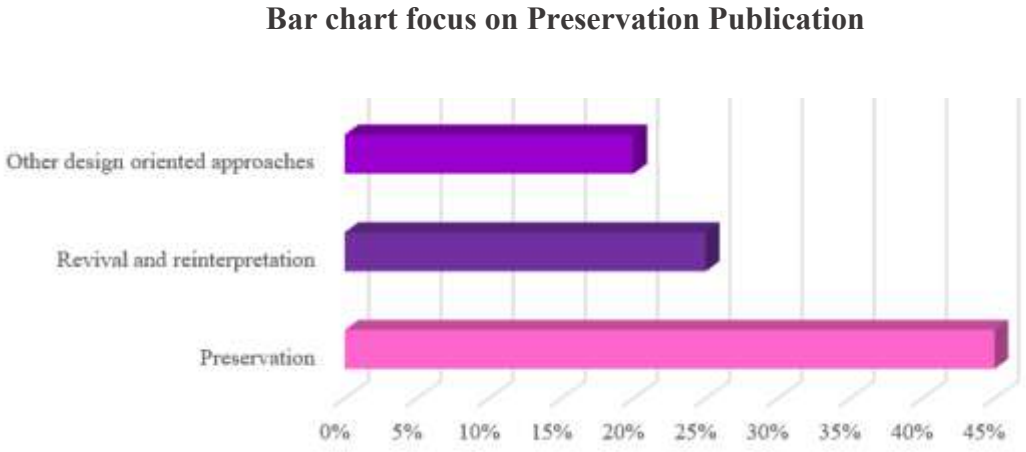


Figure 5: Fifth Literature Review Data

Based on the fifth literature review, data regarding the preservation publication focus, the academic landscape splits into three primary methodological tracks.
The largest share of the analyzed research, accounting for roughly 46% of the corpus, centers squarely on preservation. This substantial group—which includes literatures [4], [5], [6], [10], [24], [30], [35], [36], [38], [40], [41], [42], [43], [44], [48], [49], [50], [51], [52], [53], [55], [57], and [59] dedicates itself to ensuring long-term semantic archiving and establishing institutional data permanence. Scholars in this track focus heavily on strict metadata accountability and perfecting the complex technical workflows required for physical-to-virtual safeguarding.
Meanwhile, a second significant wave of research, capturing about 26% of the focus, shifts the conversation toward revival and reinterpretation. Represented by literatures [1], [2], [3], [8], [9], [15], [16], [17], [18], [32], [33], [34], [37], [39], [47], [54], and [60], this approach is dedicated to translating historical visual styles into active, generative design environments. Rather than keeping history under glass, these studies look for innovative ways to restructure traditionally static museum elements into fluid, highly accessible public narratives.

Finally, the remaining 21% of the literature explores other design-oriented approaches. This systems-focused category comprising literatures [7], [11], [12], [13], [14], [19], [20], [21], [22], [23], [25], [26], [27], [28], [29], [31], [45], [46], and [58] moves into deeper technical and structural territories. Instead of focusing purely on cultural heritage curation, these works spend their energy evaluating material structural engineering, modeling complex algorithmic query logics, optimizing UI/UX tracking environments, and validating overall system behaviors.

2. Methodology

This research employs a multi-faceted qualitative methodology that bridges traditional craftsmanship with advanced computational design. The framework is structured to transition systematically from primary physical data to complex three-dimensional visualizations. By grounding the digital process in tactile, culturally significant practices, the study ensures a continuity between historical artistic methods and modern digital applications. The process is divided into three core stages: analog prototyping, digital reconstruction, and spatial integration via Digital Twin technology.

In alignment with academic integrity guidelines and to ensure full transparency, generative artificial intelligence (AI) tools (Gemini, Irena AI, Chat GPT)were selectively incorporated into specific phases of the research methodology. Specifically, the text-to-image AI platform was utilized to generate initial visual assets and abstract design concepts during the prototyping phase, providing a creative foundation for the digital pattern configurations. Additionally, AI-driven language models were used as drafting and proofreading support to refine the clarity, structure, and academic phrasing of the text. Crucially, all AI-assisted outputs—both visual and textual—underwent rigorous manual verification, factual cross-referencing, and critical evaluation by the author to ensure complete accuracy, original context integration, and alignment with the thesis objectives.

In this study, a Digital Twin is defined as a dynamic, high-fidelity virtual replica of a physical space or object that maintains a functional link with its real-world counterpart[111]. Unlike a static 3D model, a Digital Twin serves as a "living" repository for both tangible geometry and intangible metadata[112]. [113]In the context of cultural heritage, this technology allows traditional motifs to be tested, manipulated, and experienced within simulated environments before physical implementation. This ensures that the integration of ancient semiotic structures into modern spaces is both mathematically accurate and culturally resonant.[114]

A digital twin is a dynamic virtual representation of a physical object, system, or process that continuously synchronizes with its real-world counterpart through real-time data exchange, enabling simulation, monitoring, analysis, and optimization.[115]

[111] Matta 2024, p. 8
[112] Pasupuleti 2025, p. 52
[113] Grieves & Vickers (2017), pp. 85-113
[114] Batty, 2018, pp. 317-320; Grieves & Vickers, 2017, p. 13
[115] Grieves & Vickers, 2017, pp. 91–94

Figure 1: Iranian AI traditional patterns digital twin. Real-time virtual replica of a Persian carpet loom integrating advanced digital mapping with traditional craftsmanship. (Source: Niu, 2025, pp. 3–5; AI-generated visualization).

Beyond the realm of cultural heritage, the application of Digital Twin technology has fundamentally reshaped several global industries by replacing static observation with dynamic, real-time simulation. In Smart Manufacturing, for instance, the technology has moved from a conceptual tool to a core operational framework; a notable example is BMW's use of the NVIDIA Omniverse. By building full digital replicas of production lines, engineers can simulate everything from robot paths to worker ergonomics before any physical construction begins, effectively reducing planning time by nearly 30%. [116]This shift ensures that physical assets are optimized long before they are manifested in reality[117].

A similar transformation is evident in Healthcare and Personalized Medicine, where patient-specific models of organs allow for a "living" approach to surgery[118]. Through systems deployed by Philips, surgeons can ingest MRI and CT data to create a cardiac digital twin, allowing them to test drug responses or plan complex valve replacements on a virtual heart before entering the operating room. This reduces procedure risk and optimizes recovery, proving that the digital twin is not just a visual aid but a life-saving predictive tool.

On a larger scale, Urban [119]Infrastructure and Smart Cities utilize these replicas to manage the complexities of modern living. "Virtual Singapore" serves as a benchmark in this field, integrating real-time data from transport and weather sensors to model pedestrian flow and simulate emergency

[116] Grieves & Vickers, 2017, pp. 90-94
[117] Namer and Tornielli 2025, p. 55
[118] Niu, 2025, pp. 10-11
[119] Florido-Benítez 2025

evacuation routes[120]. This capability to sync with IoT sensors transforms a city into a responsive, data-driven environment.

This logic extends to Energy Systems, where offshore wind farm operators like Ørsted use twins to ingest sea condition data and adjust turbine blade angles in real time, boosting energy yields by up to 10%.[121]

Finally, in the Automotive and Aerospace sectors, the lifecycle of a product is now tracked through its digital counterpart. Tesla, for example, maintains a digital twin for every vehicle sold, using telemetry data to simulate edge-case driving scenarios and deploy software updates remotely. Across all these fields, the common thread is the transition from a "static archive" of data to a "functional simulation," a methodology that this thesis adopts to ensure that traditional motifs remain viable and interactive in the digital age[122].

The qualitative methodology entails the creation of a final two-dimensional model or prototype using manual drawing techniques, then 3D modeling.

The methodology of this research involves the integration of traditional patterns to generate new and visually engaging designs through the use of digital design software such as CorelDRAW, Adobe Illustrator, and, in certain cases, Adobe Photoshop. These newly developed patterns are subsequently applied to objects or spaces that possess intrinsic value but lack aesthetic appeal, or that offer potential for redesign. The redesign process employs simple two-dimensional and three-dimensional digital models created using the aforementioned software, as well as Blender, with careful consideration to ensure that the essential characteristics of the traditional patterns are preserved rather than entirely transformed[123].

This study adopts a multi-faceted methodological approach that combines theoretical research with practical digital modeling and design implementation. A key component of the process is the digital reconstruction and reinterpretation of traditional patterns. The research initially began with hand-drawn prototypes on canvas, which serve as the physical foundation for the design concepts[124]. These prototypes, created using acrylic paints, embody the core objective of reintroducing traditional motifs into contemporary contexts. By grounding the digital design process in tactile, culturally significant

[120] Batty, 2018, pp. 317-319
[121] Grieves & Vickers, 2017, pp. 105-110
[122] Niu, 2025, p. 12
[123] Wieme, Baer, and Hoebeke 2025, p. 56
[124] Hasan and Crawford 2025, p. 66

craftsmanship, the methodology ensures continuity between traditional artistic practices and modern digital applications.

Digital modeling and design development will be conducted primarily using CorelDRAW and Adobe Photoshop. CorelDRAW will be employed for its advanced vector-based capabilities, enabling precise geometric reconstruction, scaling, and refinement of pattern structures. Adobe Photoshop will support texture development, color correction, and the integration of patterns into realistic spatial visualizations.

Adobe Illustrator will serve as an additional vector-based tool, particularly effective for generating intricate graphic elements, detailed line work, and seamless pattern repetitions. If three-dimensional modeling becomes necessary, Blender will be utilized due to its versatility and open-source functionality.

This is a Simple draft Process Mapping of first phase of methodology which represents the initial phase of the overall methodology, focusing on the transformation of primary data into two dimensional prototypes that enable progression to the subsequent phase of the research framework:

2.1 First Phase :

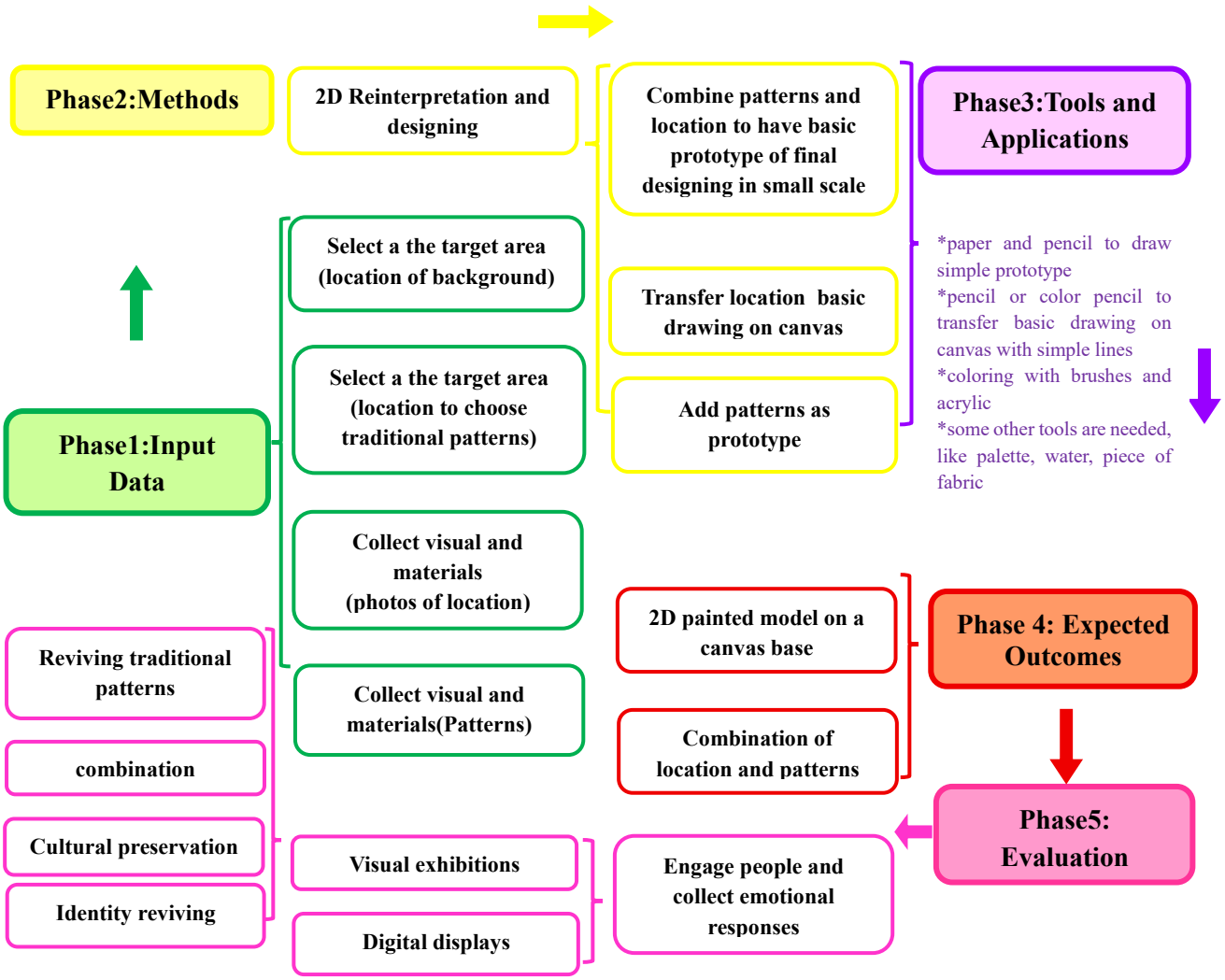


Figure 6: First Methodology Steps

The second designed methodology illustrates how the same methods can be applied in different ways across multiple case studies. While continuing to follow a two-dimensional approach, these steps collectively establish the appropriate framework for advancing toward the final stage of the methodology:

2.2.Second Phase :

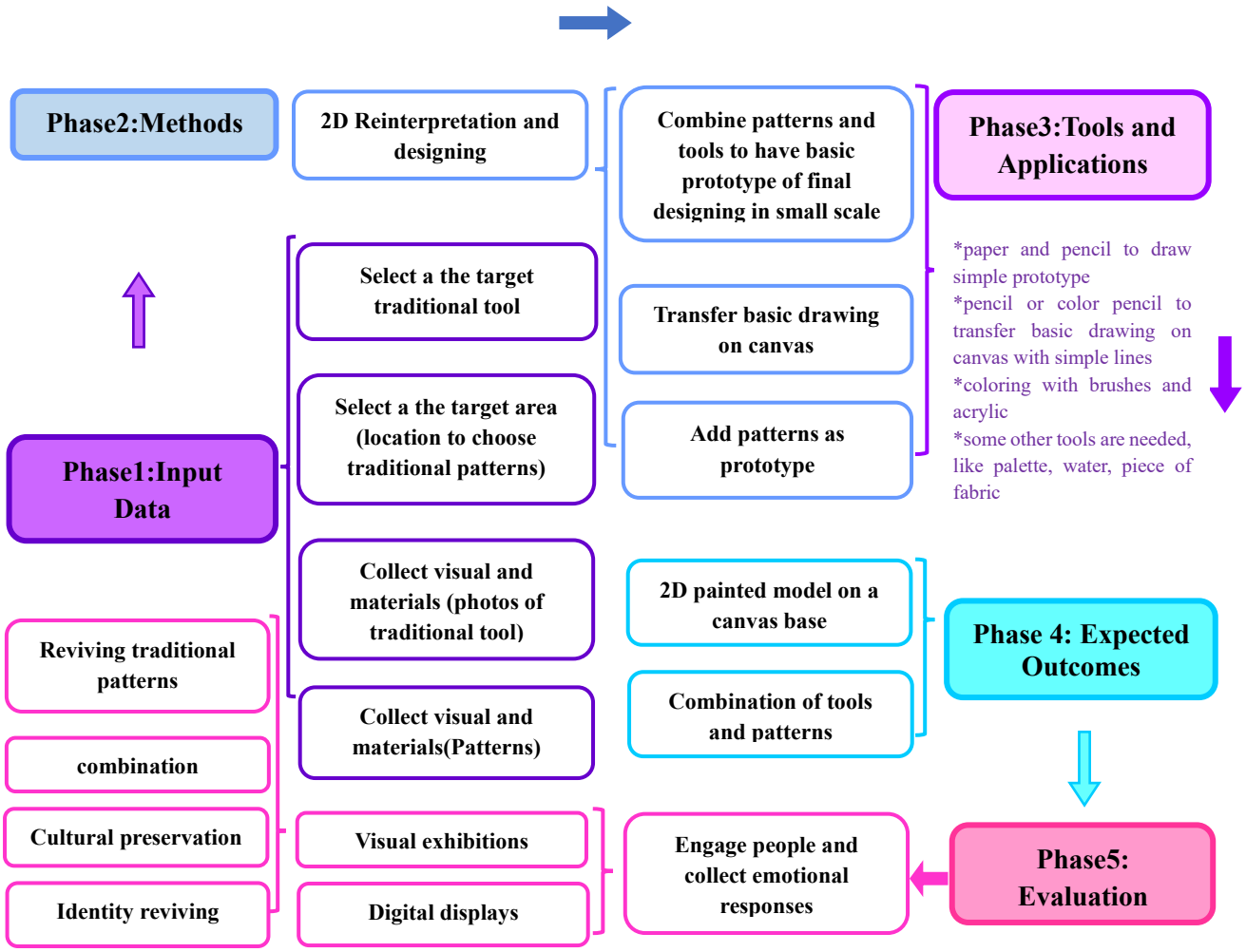


Figure 7: Second Methodology steps

Collectively, this suite of software enables an in-depth exploration of how traditional patterns can be manipulated, adapted, and embedded within diverse digital design contexts. The digital modeling process will further demonstrate the transformation of two-dimensional motifs into three-dimensional applications within digital twin environments. When simplified three-dimensional representations of architectural forms or selected spatial case studies are required, Blender will be the preferred modeling platform. However, where efficient, three-dimensional forms may also be produced using the previously mentioned design software. Through this approach, digital twins will function as experimental platforms for testing the spatial integration of traditional patterns while maintaining their cultural identity.

This final phase of the methodology focuses on transforming two dimensional and primary data into thre dimensional models, which offers greater effectiveness and clarity for audiences compared to the preceding phases:

2.3.Third Phase:

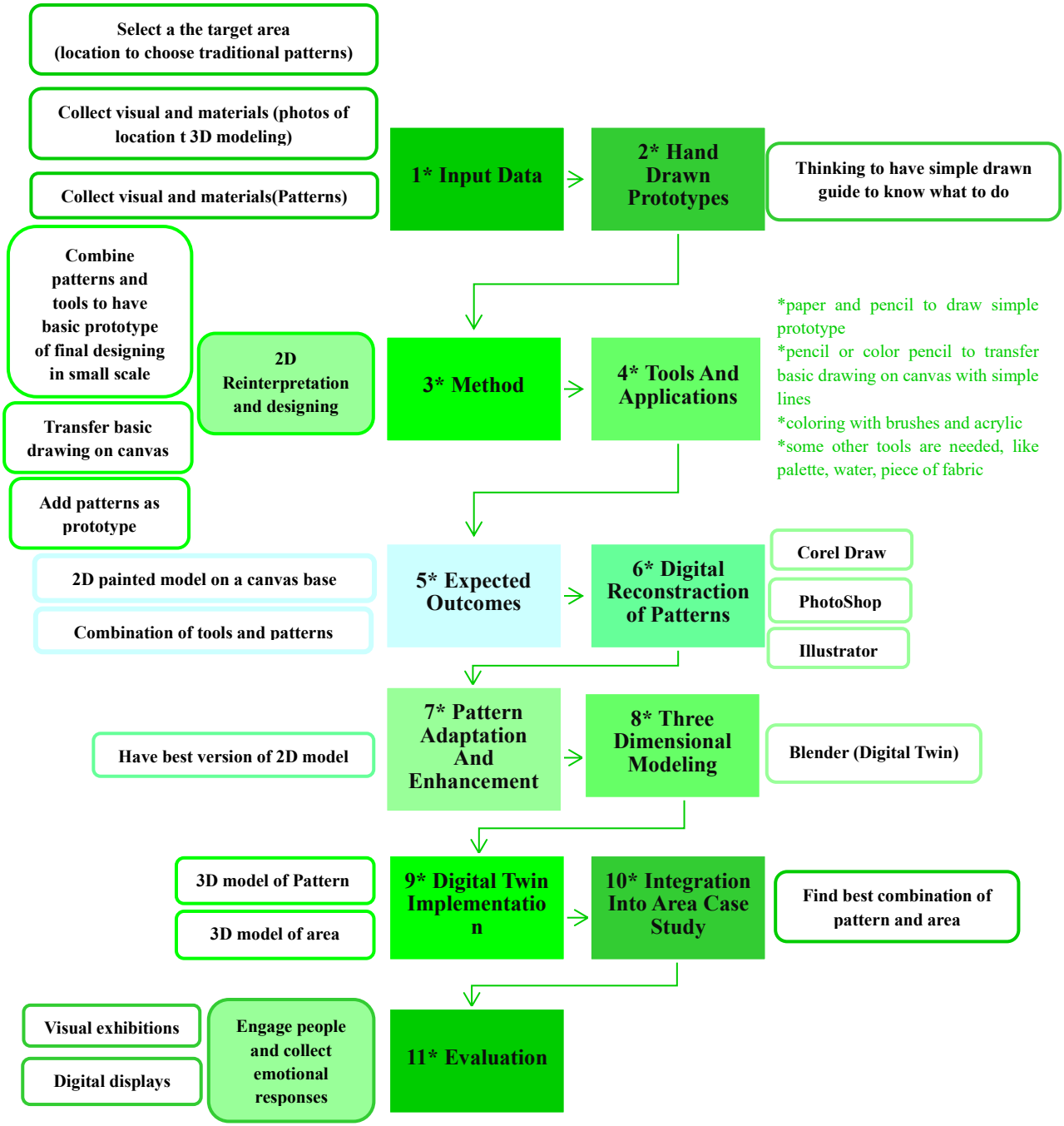


Figure 8: Third Methodology Steps

In the specialized field of Digital Humanities and Art, Digital Twin technology has evolved beyond simple 3D modeling to become a dynamic tool for cultural continuity and immersive engagement. Within Cultural Heritage Preservation, high-fidelity models are now synchronized with environmental sensors to monitor structural degradation in real time. A landmark operational precedent is the European Union's Horizon 2020 INCEPTION project, which pioneered an inclusive, open-standard Semantic Web platform for Heritage Building Information Modeling (H-BIM). This

framework integrates 3D laser scans with time-dynamic data and non-destructive structural sensors to diagnose and simulate heritage conservation strategies before physical intervention. By capturing both geometric precision and qualitative semantic metadata, such projects demonstrate how historical monuments can be preserved not just as static stone structures, but as permanent, data-rich, and interactive archival records. [125]

The technology is similarly redefining the Museum and Exhibition Experience. Institutions such as the Smithsonian and the British Museum have pioneered the use of cloud-synced virtual replicas. To expand these initiatives on a macro level, the European Union's Horizon 2020 INCEPTION project established an open-standard Semantic Web framework that allows museums to enrich 3D digital replicas with historical and structural metadata. This inclusive platform enables interactive storytelling via AR/VR while simultaneously logging engagement metrics, helping curators balance public accessibility with the preservation of fragile physical objects.[126]

This shift toward the "experience-based" model is further amplified in Live Performance and Generative Art. For example, the Refik Anadol Studio treats the digital twin as a "responsive data organism," ingesting real-time urban and environmental data to create evolving visual environments that reinterpret reality as it unfolds[127].

An operational manifestation of this methodology is seen in the project WDCH Dreams (Los Angeles Philharmonic), where the studio transformed the Walt Disney Concert Hall into a living architectural digital twin. The workflow consists of a specific computational pipeline: (1) harvesting massive digital archives including 45 terabytes of historical audio, visual, and text data, alongside real-time architectural sensor outputs, (2) applying machine learning algorithms to categorize and vectorize the qualitative metadata, and (3) deploying deep neural networks to translate these data patterns into dynamic, three-dimensional generative projections cast across the building's physical facade. Through this process, millions of distinct archival memories are synthesized into a real-time, responsive spatial installation.

Furthermore, digital twins have become indispensable for archival research and historical simulation. The Pompeii I.14 Project demonstrates how integrating stratigraphic excavation data with localized climate and geospatial models allows scholars to simulate historical trade flows, structural changes, and daily life over time without disturbing the physical site. By shifting from static 3D models to dynamic cloud-synchronized databases, researchers can evaluate how spatial anomalies and material

[125] Maietti et al., 2022
[126] Niu, 2025, pp. 48–50
[127] Manovich, 2001, pp. 215–218

degradation respond to environmental variables, establishing a risk-free virtual environment for long-term heritage analysis.[128].

This non-invasive methodology extends to Material Conservation, where the Van Gogh Museum utilizes spectral imaging to build twins of specific brushwork and pigments. By simulating how colors age under varying conditions, conservators can develop precise preservation strategies[129]. Ultimately, these applications prove that Digital Twins act as a living bridge, ensuring that cultural heritage remains a functional, interactive asset in a digital-first world.

The conceptual foundation of this study emerged from a phase of "controlled serendipity" during an exploratory photographic survey I conducted across Venice. Designed as a hands-on visual methodology to map the city's dense layers of historical texture, my fieldwork focused on capturing the dialogue between macro-architectural relationships such as the rhythmic, repetitive geometry of historic Venetian facades and the micro-decorative details embedded within local cultural sites[130].

During this documentation process, an unexpected "catalyst of chance" occurred when a temporary processing glitch on my mobile capture device caused two distinct photographic references to freeze and merge within the image cache. One photograph captured physical, stone architectural elevations, while the other detailed highly intricate, traditional textile motifs. Rather than treating this digital artifact as a disposable error, I recognized it as an immediate, striking visual proof-of-concept. The accidental overlay laid bare a deep structural and geometric affinity between the spatial syntax of Western historic architecture and the mathematical rhythms of Eastern ornamental design. This unexpected synthesis became the empirical spark for my study's entire computational pipeline, prompting me to move past the passive observation of cross-cultural parallels and instead actively build digital twin workflows designed to deliberately merge disparate cultural geometries[131].

Far from being a mere technical error, this accidental double-exposure functioned as an immediate visual proof-of-concept. The overlay revealed an unexpected structural and geometric affinity between the spatial syntax of Western architecture and the mathematical rhythm of Eastern design traditions. This serendipitous synthesis provided the empirical spark for the research pipeline, prompting a systematic inquiry into how digital twin workflows can deliberately merge disparate cultural geometries into unified, contemporary architectural environments.

[128] Moretti, 2013, pp. 105–108
[129] Niu, 2025, pp. 52–54
[130] Ivi, pp. 18–20
[131] Ivi,, pp. 18–20

This unintentional overlap served as a visual prototype, revealing a compelling "visual dialogue" where patterns merged seamlessly with architectural surfaces. This moment demonstrated the potential of Projection Mapping and Digital Overlay as tools for cultural reintegration. It prompted a shift from mere documentation to an intentional research framework: exploring how cultural motifs can be embedded within spatial contexts to revive cultural identity.

2.4. Input Data

The research begins with a physical "Input Data" phase. Before entering the digital environment, hand-drawn prototypes are created on canvas using acrylic paints, brushes, and traditional palettes. These paintings serve as the "micro-vision" of the project, allowing for an intuitive exploration of color, line work, and pattern composition.

By utilizing paper and pencil for initial drafting and canvas for final 2D prototypes, my methodology captures the "intangible" qualities of traditional patterns. In this context, intangibility refers to the fluid, non-quantifiable dimensions of heritage design specifically its emotional resonance, cultural symbolism, and the organic irregularities born of human craftsmanship that standard computational tools often fail to register. Because purely automated digitization risks reducing complex cultural motifs to sterile, mathematical coordinates, this initial physical stage acts as a vital preservation step.

This approach aligns with broader cultural heritage frameworks, which emphasize that the value of traditional motifs lies not just in their physical geometry, but in the living, intangible knowledge and spirit they convey[132]. By engaging in manual drafting before entering a digital workflow, I can internalize the rhythm and historical weight of the motifs through tactile practice. This ensures that the essential character and emotional depth of the design are deeply anchored and preserved before they undergo digital translation into a parametric environment[133].

The transition from a physical sketch to a digital model isn't just about copying a shape; it is a deliberate process of "reverse-engineering" the soul of the pattern. In practice, this means I do not merely trace lines or rely on automated image-to-vector software, which often flattens the structural integrity and historical nuances of traditional art. Instead, I treat the physical drawing as a complex geometric puzzle, systematically deconstructing the traditional motif into its foundational logic, proportional grids, and mathematical symmetries. This method of breaking down visual designs into

[132] UNESCO, 2003
[133] Dortacio, 2020

explicit rule sets and spatial syntax allows me to decode the structural "DNA" or design grammar that guided the original artisans[134].

Once this underlying grammar is fully understood, the pattern is digitally rebuilt within a parametric framework. This computational translation allows the historic motif to transition from a static, rigid artifact into an adaptive, dynamic system. By reverse-engineering the design in this manner, I ensure that its authentic visual rhythm and cultural soul are preserved, while simultaneously granting the geometry the necessary flexibility to scale, morph, and integrate organically into contemporary, data-rich architectural models[135].

By starting with paper and pencil, I can deconstruct the complex geometry of motifs like the Girih or the Koru, identifying the mathematical rules and narrative flow that a digital scan might overlook. This hand-drafting stage forces a slow, rhythmic engagement with the work, allowing me to capture the subtle "imperfections" and organic warmth that give traditional art its emotional weight.

Once these intangible qualities are understood through the tactile experience of drawing and painting on canvas, they act as a blueprint for the digital phase. This ensures that when the motif is finally integrated into a 3D Digital Twin, it isn't just a sterile piece of data, but a living piece of heritage that retains its cultural resonance and human scale. Essentially, the analog prototype serves as the "DNA" that keeps the digital version grounded in its original history.

Following the physical creation of motifs, the methodology moves into Digital Reconstruction. This phase utilizes a suite of professional design software to transform 2D prototypes into scalable assets:

The software pipeline moves from geometric reconstruction to refined vector manipulation and spatial contextualization. First, CorelDRAW is employed for its advanced vector-based capabilities, enabling precise geometric reconstruction and scaling of intricate pattern structures. Building upon these reconstructed forms, Adobe Illustrator is used to refine detailed line work and generate the seamless repetitions required for large-scale architectural applications. Finally, Adobe Photoshop facilitates texture development, color correction, and initial 2D spatial visualizations by masking the patterns directly onto photographic backgrounds of the target locations.

The final and most innovative phase focuses on transforming two-dimensional data into three-dimensional models. To resolve the structural ambiguity of this transition, the methodology is

[134] Stiny, 2006, p. 120
[135] Bolognesi & Garagnani, 2022, p. 34

explicitly structured around three distinct designed shapes that mark the pattern's geometric evolution. The process originates with the First Shape (the Analog Graphic Profile), which captures the raw, hand-drawn outline and organic symmetry of the motif. This profile is then systematically translated into the Second Shape (the Parametric Modular Vector), where the design is converted into a flexible, two-dimensional digital grid defined by mathematical variables and repeating border constraints. Finally, the workflow culminates in the Third Shape (the Volumetric Spatial Component), where the two-dimensional vector data is extruded, mapped, and simulated within a three-dimensional environment. By organizing the methodology around these three progressive geometric states, this stage offers greater clarity for the audience, shifting from a flat archival study to a functional simulation of how reinterpreted cultural patterns physically interact with three-dimensional volumes and architectural spaces.

When three-dimensional representations of architectural forms are required, Blender serves as my primary modeling platform. Within this environment, the digitized patterns are integrated into "digital twins"—highly precise, experimental digital replicas of real-world spaces. Rather than functioning as static visual backdrops, these twins serve as active, virtual testing laboratories. This computational environment allows for the rigorous evaluation of three core spatial parameters:

Materiality and Light Interaction: By leveraging Blender’s physically-based rendering engines, I can simulate how different material textures—such as stone, wood, or glass—interact with complex traditional motifs. This includes testing how ambient light, shadow casting, and real-world lighting conditions alter the visibility and aesthetic depth of the patterns across different times of day.

Structural Scale and Proportion: The platform enables me to dynamically scale and tessellate the motifs across complex architectural volumes, such as columns, arches, or expansive facades. This ensures that the mathematical rhythm of the design maintains its structural harmony and visual balance when scaled from a micro-decorative detail to a macro-structural installation.

Spatial Perception and Human Scale: By navigating the digital twin through a simulated human eye-level camera, I can evaluate the immersive qualities of the redesigned space. This allows me to test how the reinterpreted patterns influence the depth perception, movement, and emotional resonance of a user experiencing the environment from a first-person perspective.

Through these simulations, the digital twin bridges the gap between historical archival data and contemporary architectural reality, providing an empirical framework to refine the patterns before any physical application.

1. **Spatial Harmony:** How motifs interact with light, shadow, and architectural scale.
2. **Hybrid Compositions:** The creation of immersive, intercultural environments where the pattern and the location exist in a unified 3D space.

By generating innovative reinterpretations of traditional assets, this study aims to move beyond static archiving. [136]The objective is to utilize digitized heritage assets to transform public and private spaces into immersive, intercultural environments. This approach ensures that environments maintain a robust connection to cultural identity while simultaneously embracing contemporary design and technological innovation.

The objective is to utilize these existing, survey-documented heritage assets—specifically the newly digitized Persian textile motifs and Venetian architectural elements—to transform public and private spaces into immersive, intercultural environments. This transformation is achieved through the deployment of digital twins that overlay these historical semiotic structures directly onto modern architectural grids. This process uses high-fidelity 3D modeling and projection mapping to create a "living" spatial experience where users can interact with the traditional motifs as functional design elements rather than static displays[137].

The why behind this approach is rooted in the need to counter the "cognitive fragmentation" of the digital age. In this context, cognitive fragmentation refers to the psychological and cultural disruption caused by constant exposure to rapid, disconnected digital streams, which shatter the human attention span and alienates individuals from their physical and historical environments[138]. This digital saturation often results in a shallow engagement with information, severing the deep, continuous threads of historical awareness. By integrating these hybrid motifs directly into everyday environments, this research aims to provide a continuous, subconscious connection to cultural memory, countering digital alienation through spatial design. This ensures that modern spaces maintain a robust connection to cultural identity while simultaneously embracing contemporary design and technological innovation. Such environments serve as "cultural anchors", [139]bridging the gap between ancient traditions and modern audiences to prevent the loss of intangible heritage in a globalized society[140].

[136] Jouan, P., & Hallot, P, pp. 2-10 (2020), Manovich (2001), pp. 213-243
[137] Niu, 2025, pp. 3-5
[138] Carr, 2020, p. 2-10
[139] Moretti, 2013, p. 98-99
[140] Niu, 2025, p. 12

While supported by Ca' Foscari University, this research acknowledges that museums, heritage sites, galleries, and academic publications serve as vital stakeholders. These institutions are currently witnessing a shifting landscape where traditional, static displays face a rising public disregard, largely because contemporary audiences increasingly favor fragmented, entertainment-oriented digital consumption over passive observation[141]. This critical shift challenges museums to find new ways of capturing deep engagement in a highly distracted society[142]. To counter this institutional alienation, this thesis proposes a sustainable framework for future collaborations that reinterprets traditional patterns through immersive technology and responsive design pipelines[143]. By translating archival motifs into active spatial environments, this model aims to revitalize public interest, transforming passive viewers into active participants and ensuring the survival of cultural heritage in a digital-first world.

The validation of this methodology relies on established precedents in immersive exhibition design, digital archival practices, and contemporary media theory. Looking first at the rapid rise of "experience museums," successful international precedents like the Atelier des Lumières in Paris or the Van Gogh Immersive Experiences demonstrate how traditional art can be dynamically revitalized for modern audiences. By transforming static paintings into 3D, room-scale projections, these institutions have successfully attracted younger demographics who typically bypass traditional galleries, proving that spatial immersion can break down barriers to classical art consumption.

Building upon this spatial approach, digital recontextualization initiatives show how digital tools can push past the limitations of the physical archive. A prime example is the Victoria and Albert Museum's "World of Patterns" initiative, which uses digital workflows to move beyond static museum cases, allowing users to see how ancient motifs can be directly applied to modern lifestyle and architectural design. This shift from passive observation to active contextualization directly supports the thesis that modern users engage more deeply when they can visualize the practical utility and scalability of a historical motif within a contemporary setting[144].

This practical evolution is deeply anchored by a robust theoretical framework. Lev Manovich's foundational concepts on "Spatial Montage" (The Language of New Media) and Franco Moretti's work on "Distant Reading" (Distant Reading Framework) collectively support the idea that complex cultural data must be visualized in new, interactive, and macro-level spatial formats to

[141] Katifori et al., 2020 , p. 76
[142] Moretti, 2013, pp. 103-120
[143] Niu, 2025, pp. 45-58
[144] Ivi,, pp. 50-55

remain relevant in a data-rich society. Furthermore, recent studies on digital twin integration in cultural heritage by Jouan and Hallot (2020) in Digital Twins for Cultural Heritage Management (Springer Link) argue that heritage stakeholders must undergo a critical paradigm shift. To remain sustainable in the 21st century, these institutions must transition from acting purely as static "guardians of physical objects" to becoming dynamic "curators of digital experiences."

2.5.The ongoing worldwide projects according to the fields that are mentioned above:

To map the global landscape of emerging technologies in the humanities, it is necessary to divide ongoing initiatives into distinct categories. Digital twin technology is not a one-size-fits-all solution; a system designed to monitor the structural engineering of an ancient monument requires completely different data streams, sensors, and operational logic than a system built for immersive public education or live artistic performance. By separating these projects into specialized categories, we can analyze how computational frameworks are uniquely tailored to match specific preservation, presentation, and creation goals.

The first major field focuses on safeguarding the physical integrity of historical monuments. These initiatives prioritize engineering, material stability, and long-term environmental monitoring, using real-time sensor loops to predict structural failures before they happen.

Table 1: Table of Cultural Heritage Preservation & Restoration

Project	Institutions/Partners	Status & Twin Features
Colosseum Digital Twin & Structural Monitoring Network	Italian Ministry of Culture, Politecnico di Milano, Siemens, Enel	Ongoing since 2022. Integrates IoT strain gauges, microclimate sensors, and drone photogrammetry into a live 3D twin. Simulates seismic stress, visitor load, and material fatigue to guide phased restoration.
Historic England Digital Twin for Heritage Assets	Historic England, University of Cambridge, Autodesk	Active pilot (2023–2026). Creates dynamic twins of Grade I/II* buildings using LiDAR, BIM, and environmental sensors. Tracks moisture, thermal cycling, and structural movement to predict decay and optimize conservation budgets.

Project	Institutions/Partners	Status & Twin Features
Angkor Archaeological Park Digital Twin	APSARA Authority, UNESCO, Tokyo University, CyArk	Ongoing phase 2 (2024–2027). Combines pre-restoration scans with real-time groundwater, vegetation encroachment, and tourist flow data. Runs erosion and structural stability simulations for temple conservation planning.

A separate table is required for museum and exhibition spaces because the core objective shifts from structural civil engineering to public accessibility and curatorial management. These twins do not just monitor materials—they track human interaction, visitor logistics, and real-time environmental exposure to optimize how public audiences engage with curated collections.

Table 2: Table of Immersive Museum & Exhibition Experiences

Project	Institutions/Partners	Status & Twin Features
Rijksmuseum Digital Twin & Visitor Flow Simulator	Rijksmuseum, TU Delft, Microsoft Azure	Live since 2023. Cloud-synced twin of galleries updates with real-time foot traffic, humidity, and light exposure. Powers AR visitor guides, dynamic exhibit routing, and conservation alerts for light-sensitive works.
The Met's 3D Collection & Virtual Gallery Twin	The Metropolitan Museum of Art, Google Arts & Culture, Matterport	Ongoing expansion (2022–present). High-fidelity twins of 20,000+ objects + gallery spaces. Continuously ingests conservation reports, engagement metrics, and environmental data to test virtual exhibition layouts and reduce physical handling.
Egyptian Museum Cairo Digital Twin (Grand Egyptian Museum Integration)	Ministry of Tourism & Antiquities, Siemens, Fraunhofer IGD	Active deployment (2024–2026). Twin of artifact storage + exhibition halls syncs with climate control, security, and visitor analytics. Enables remote curator access, predictive conservation, and VR public tours without physical exposure.

Moving away from static historical assets, the third category explores the intersection of real-time human movement and generative design. These projects are isolated into their own table because they utilize digital twins as fluid, creative co-performers, capturing live biometrics and motion data to drive contemporary audio-visual art installations and performances.

Table 3: Table of Live Performance & Generative Art

Project	Institutions/Partners	Status & Twin Features
Wayne McGregor Studio × Google Arts & Culture: AI Choreography Twin	Wayne McGregor, Google DeepMind, Rambert Dance Company	Ongoing R&D (2023–present). Digital twin of dancers' motion capture + biometric data feeds generative AI to create evolving choreographic sequences. Used in live performances where the twin adapts to audience sound/heat data in real time.
MIT Media Lab: Opera of the Future – Digital Twin Performers	MIT Media Lab, IRCAM, Ensemble Modern	Active research phase (2024–2025). Twin of vocalists/instruments ingests breath, muscle tension, and acoustic feedback to drive responsive visual/audio environments. Tested in live installations where the twin "learns" performer habits and generates counter-melodies.
Random International: "Swarm Intelligence" Adaptive Installations	Random International, Ars Electronica, TU Berlin	Touring/ongoing (2023–present). Physical installations paired with digital twins that mirror visitor movement, ambient sound, and weather data. The twin runs agent-based simulations that alter light, sound, and mechanical responses in real time.

We then isolate archival research and historical simulation because these systems handle conceptual, text-based, and historical data rather than monitoring a live physical object. These twins act as virtual time machines, running algorithmic agent-based models to test archaeological hypotheses, historical trade routes, and climate impacts based on fragmented data from the past.

Table 4: Table of Archival Research & Historical Simulation

Project	Institutions/Partners	Status & Twin Features
Virtual Angkor Project (Climate & Trade Simulation Twin)	Monash University, University of Sydney, APSARA	Active phase 2 (2024–2026). Dynamic 3D twin of 13th-century Angkor integrates hydrological models, archaeological finds, and paleoclimate data. Researchers simulate monsoon impacts, trade route shifts, and urban expansion without disturbing sites.
Rome Reborn: Digital Twin of Imperial Rome (UCLA/IDA)	UCLA, Institute for Digital Archaeology, University of Bologna	Continuously updated (2023–present). Twin syncs new excavation reports, LiDAR surveys, and historical texts. Runs agent-based simulations of population movement, supply chains, and structural decay to test archaeological hypotheses.
Silk Road Digital Twin Network	UNESCO, University of Tokyo, Chinese Academy of Social Sciences	Ongoing consortium project (2024–2028). Integrates caravan route data, climate archives, and artifact provenance into a multi-node twin. Enables cross-institutional simulation of cultural exchange, material degradation, and route viability under historical climate shifts.

The final international tier focuses strictly on material science, chemical behavior, and artistic intent. This database approach is separated from structural architectural twins because it operates on a microscopic and chemical level—tracking pigment aging, binder decay, and software obsolescence to document how modern and traditional materials degrade over time.

Table 5: Table of Artistic Process Documentation & Material Conservation

Project	Institutions/Partners	Status & Twin Features
Tate's Digital Conservation Twin Initiative	Tate, University of Cambridge, Getty Conservation Institute	Active since 2023. Creates material/process twins of modern/contemporary works using hyperspectral imaging, XRF, and studio interviews. Simulates pigment aging, binder degradation, and lighting impacts to guide conservation and artist estate documentation.

Project	Institutions/Partners	Status & Twin Features
Getty Conservation Institute: Material Science Digital Twin Database	Getty Conservation Institute, MIT, Rijksmuseum	Ongoing (2022–present). Twin library of historical/contemporary art materials continuously updated with accelerated aging tests, environmental exposure data, and conservation interventions. Used globally to predict degradation pathways and test cleaning protocols virtually.
MoMA Contemporary Art Material Tracking Project	MoMA, NYU Conservation Center, Siemens	Pilot/active (2024–2026). Digital twins of installation-based and time-based media artworks sync with sensor data from storage/exhibition environments. Tracks chemical off-gassing, LED decay, and software obsolescence to plan migration and preservation strategies.

2.6. The ongoing Italian projects according to the fields that are mentioned above:

Narrowing the scope to the Italian academic and institutional landscape, a parallel separation of tables is carried out for the exact same reasons. Italy's unique density of fragile, highly localized historical architecture and material heritage requires dedicated regional frameworks funded by national initiatives like the PNRR.

Just like the international overview, the first category isolates large-scale, structural site management where the immediate danger of environmental stress, subsidence, and seismic activity requires high-fidelity physical engineering feedback loops.

Table 6 : Table of Cultural Heritage Preservation & Restoration

Project	Institutions	Twin Features & Status
Colosseo Digital Twin & Structural Monitoring Network	Parco Archeologico del Colosseo, Politecnico di Milano, Siemens Italy, CNR-ITC	Ongoing. IoT strain gauges, microclimate sensors, and drone LiDAR sync to a live 3D model. Simulates seismic stress, visitor load, and material fatigue to guide phased restoration.

Project	Institutions	Twin Features & Status
Venezia Storica Digital Twin	Comune di Venezia, IUAV University, CNR-ISMAR, MOSE Consortium	Active 2023–2026. Real-time twin of historic palazzos & canals tracking subsidence, humidity, tidal stress, and salt crystallization. Prioritizes conservation interventions and simulates restoration outcomes.
Pompei Digital Twin & Conservation Simulator	Parco Archeologico di Pompei, CNR-IIT, Univ. Federico II	Ongoing. Continuous photogrammetry + environmental/structural sensors feed a dynamic twin. Tests virtual restoration strategies, simulates fresco degradation, and optimizes site drainage.

The second Italian pillar addresses the public-facing platform, where cloud-synced architecture is deployed directly inside major galleries and museums to turn environmental and foot-traffic metadata into fluid visitor routing and smart public curation tools.

Table 7: Table of Immersive Museum & Exhibition Experiences

Project	Institutions	Twin Features & Status
Uffizi Digital Twin & Smart Gallery Platform	Gallerie degli Uffizi, CNR-ISMAR, Leonardo S.p.A.	PNRR-funded, active 2023–present. Cloud-synced 3D galleries ingest real-time visitor flow, light/humidity, and conservation reports. Powers AR guides, dynamic routing, and exposure alerts for light-sensitive works.
Museo Egizio Torino Digital Twin	Museo Egizio, Politecnico di Torino, Reply	Ongoing. Twin of exhibition/storage spaces with climate, security, and visitor analytics. Enables remote curator access, predictive conservation, and adaptive VR public tours without physical handling.
MAXXI Rome Adaptive Exhibition Twin	MAXXI, Sapienza Università, Accenture Italy	Active 2024–2026. Dynamic twin tracks environmental conditions and engagement metrics to simulate exhibit layouts, reduce physical handling, and optimize lighting for contemporary/time-based media.

Italian research also bridges performance spaces and live generative design. This distinct table group tracks projects where acoustics, performer biometrics, and audience feedback are modeled

dynamically to turn the digital twin into an active, responsive component of live concerts and spatial installations.

Table 8: Table of Live Performance & Generative Art

Project	Institutions	Twin Features & Status
Teatro alla Scala Acoustic & Stage Digital Twin	Teatro alla Scala, Politecnico di Milano, CNR-IENI	Ongoing R&D. Twin of auditorium + real-time acoustic, structural, and motion-capture data. Simulates sound propagation, stage mechanics, and drives adaptive lighting/visuals for live performances.
Ravenna Festival & CNR Generative Performance Twin	Ravenna Festival, CNR-ILC, Univ. Bologna	Active pilot 2023–2025. Ingests performer biometrics, audience acoustics, and ambient environmental data to generate responsive visual/audio environments in real time during concerts and installations.
Fondazione Prada Milano “Living Archive” Twin	Fondazione Prada, Politecnico di Milano, MIT Media Lab (collab)	Ongoing. Twin of exhibition spaces + artist process data feeds AI models that adapt generative installations to visitor movement, temperature, and acoustic shifts during live shows.

In the domain of historical simulation, Italian digital humanists separate their work into a unique track focused on reconstructing vanished urban spaces or simulating trading networks from raw, textual manuscript data using Natural Language Processing (NLP), entirely removing the need to touch or handle fragile archival documents.

Table 9: Table of Archival Research & Historical Simulation

Project	Institutions	Twin Features & Status
Forma Urbis Romae / Sapienza Digital Twin of Ancient Rome	Sapienza Università, CNR-ITC, MiC	Continuously updated 2023–present. Integrates new excavations, LiDAR, and historical texts into a dynamic 3D environment. Runs agent-based simulations of trade, population movement, and structural decay.

Project	Institutions	Twin Features & Status
Ercolano Digital Twin & Eruption/Conservation Simulator	Parco Archeologico di Ercolano, CNR-IIT, Univ. Oxford (Italian lead)	PNRR-funded, active 2024–2026. Twin syncs climate, structural, and archaeological data to simulate volcanic impact scenarios, material degradation pathways, and test non-invasive conservation strategies.
Archivio di Stato di Venezia Digital Twin Network	Archivio di Stato di Venezia, Ca' Foscari Univ., CNR-ILC	Ongoing 2024–2026. Twin of manuscript corpus + historical urban/climate data. Enables NLP/AI simulation of Venetian trade networks, diplomatic flows, and lost context visualization without handling fragile documents.

Finally, the localized material science and conservation track is organized into its own category. This group focuses purely on tracking microscopic changes—such as varnish degradation, chemical off-gassing, and modern technological obsolescence—to preserve the material essence of Renaissance paintings and contemporary mixed-media art alike.

Table 10: Table of Artistic Process Documentation & Material Conservation

Project	Institutions	Twin Features & Status
Gallerie dell'Accademia (Venice) Material Twin Project	Gallerie dell'Accademia, CNR-ISMAR, Univ. Padova	Active 2023–present. Hyperspectral/XRF twins of Renaissance paintings simulate pigment aging, varnish degradation, and microclimate impacts for predictive conservation and technique documentation.
Pinacoteca di Brera Digital Conservation Twin	Pinacoteca di Brera, Politecnico di Milano, Getty Conservation Institute (partnership)	Ongoing 2024–2025. Tracks material composition, historical techniques, and environmental exposure. Simulates aging under varying lighting/temperature to guide restoration and artist estate documentation.

Project	Institutions	Twin Features & Status
Fondazione Cini Contemporary Art Material Twin	Fondazione Cini, IUAV, CNR-ICMATE	Active pilot 2024–2026. Twin of modern/contemporary works + storage/exhibition sensor data. Tracks chemical off-gassing, LED decay, and software obsolescence to plan migration and preservation strategies.

2.7. Discussion

Despite the profound cultural and aesthetic value of traditional patterns and motifs, they are frequently overlooked or excluded from contemporary design workflows. This persistent disconnect contributes to a visible erosion of cultural identity, fostering a sense of placelessness in modern urban centers and public displays. Systematically integrating traditional motifs—such as geometric systems, historic ornamentation, or vernacular visual layouts—into current practices acts as a vital mechanism to preserve material heritage while enriching contemporary creative expression.

While advanced digital platforms and methodologies, including parametric modeling, generative algorithms, and artificial intelligence, offer powerful creative capabilities in theory, their physical execution on large-scale design projects faces severe real-world obstacles. These implementation barriers typically include prohibitive computational costs, structural complexity, a lack of specialized personnel, severe software interoperability issues, and institutional resistance to changing traditional studio workflows. Successfully bridging the gap between computational potential and actual on-site or physical production reality remains a significant methodological challenge.

Furthermore, creating meaningful, culturally authentic designs requires highly specialized knowledge spanning history, art theory, symbolism, historic craftsmanship, and regional design traditions. A systemic shortage of researchers and designers possessing this interdisciplinary expertise, combined with limited, fragmented engagement from traditional artisans or cultural practitioners, severely hinders the authenticity, material quality, and depth of pattern integration in modern visual and urban landscapes.

This issue is compounded by the fact that incorporating highly intricate cultural patterns into physical projects is historically time-consuming and labor-intensive. In fast-paced contemporary development environments where rapid delivery and cost-efficiency are prioritized, standard project timelines leave little room for detailed, research-driven, or handcrafted design processes. Furthermore, scaling

complex, traditional patterns to fit large-scale modern volumes without distorting their underlying geometric integrity presents a dual technical and creative bottleneck.

Finally, even the most technologically advanced or well-designed proposals risk facing resistance from local communities if they do not align with existing public values, local needs, or cultural perceptions. This friction often stems from a severe disruption of place attachment—the deep emotional bond between people and their daily environments—where digital or technological interventions can easily be perceived as alien or intrusive to a site's historical "spirit of place[145]."

Misunderstandings regarding complex cultural symbolism, conflicting aesthetic preferences, or a collective institutional fear of change can significantly diminish public support. Critical heritage research indicates that top-down, purely digital interventions frequently fail because they completely overlook the organic, social construction of heritage[146]. Without active, inclusive outreach and co-design methodologies, projects aiming to celebrate cultural identity run a high risk of low community engagement or outright public rejection.

To mitigate this limitation, current scholarship argues for a strict "Human-in-the-loop" framework. Within this approach, the Digital Twin is repositioned to serve as a collaborative, participatory platform for local stakeholders, allowing them to directly visualize, critique, and adjust parametric designs before final execution. This collaborative feedback loop ensures that technical innovation respects and preserves the community's intangible and emotional requirements[147].

[145] Manzo & Devine-Wright, 2013, pp. 45–60
[146] Niu, 2025, pp. 62-65
[147] Jouan & Hallot, 2020, pp. 8-9

3. Prototypization:

3.1. Case study

The selected cases were utilized as both instrumental and exploratory case studies. In this research, they function as instrumental case studies because they are not examined merely for their own sake, but as essential tools to gain a deeper, general understanding of how traditional motifs can be systematically digitized and adapted. By focusing on these specific instances, the cases provide critical insights into the broader challenges of heritage preservation and digital translation. Simultaneously, they serve as exploratory case studies, acting as an open-ended framework to pilot and test new parametric workflows and digital twin environments where clear, pre-existing outcomes have not yet been established in the literature.

Concurrently, the overarching case study approach is descriptive–explanatory in nature. The descriptive component is deployed to meticulously document the complex geometric rules, historical context, and structural characteristics of the existing motifs in their current state. This descriptive foundation then transitions into an explanatory analysis, which seeks to uncover the underlying causal relationships and operational logic of the digital transition. Specifically, it explains *how* and *why* specific parametric design choices, software pipelines, and digital interventions directly impact both the geometric integrity of the patterns and their ultimate acceptance by the public within a contemporary architectural space.

For this project, the case studies are organized into two primary categories: **1. Locations**, **2. Patterns**

The initial concept for this research emerged during an exploratory drawing phase aimed at developing new canvas-based artworks. As part of an ongoing personal practice, the focus was placed on depicting the surrounding living environment. During this process, photographic references of Venice were collected as visual inspiration. An unexpected technical malfunction on a mobile device resulted in the accidental overlapping of two adjacent images. One image depicted an architectural scene from Venice, while the other consisted of decorative patterns. The superimposition of these images created an unintended visual composition in which the patterns appeared to merge with the architectural surfaces.

This accidental overlap revealed a compelling visual dialogue between place and pattern, prompting the conceptual idea of intentionally combining traditional patterns with architectural locations to create new hybrid compositions. This moment marked the conceptual foundation of the research,

positioning chance visual interference as a catalyst for a structured design methodology that explores the integration of cultural patterns within spatial contexts.

This accidental overlap occurred during an initial digital modeling phase when a vector file of a traditional Persian textile motif was unintentionally superimposed across a photographic layer of a Venetian architectural site within the design workspace. This unexpected juxtaposition revealed a compelling visual dialogue between place and pattern, as the organic rhythms of the textile geometry mapped seamlessly onto the rigid structural lines of the western historical grid. This moment of chance alignment prompted the conceptual idea of intentionally combining these distinct cultural patterns with specific architectural locations to create new hybrid compositions. Consequently, this moment marked the conceptual foundation of the entire research, positioning what began as a random visual interference as the direct catalyst for a highly structured design methodology that explores the systematic integration of cultural patterns within modern spatial contexts.

The selected case study in the pattern category:

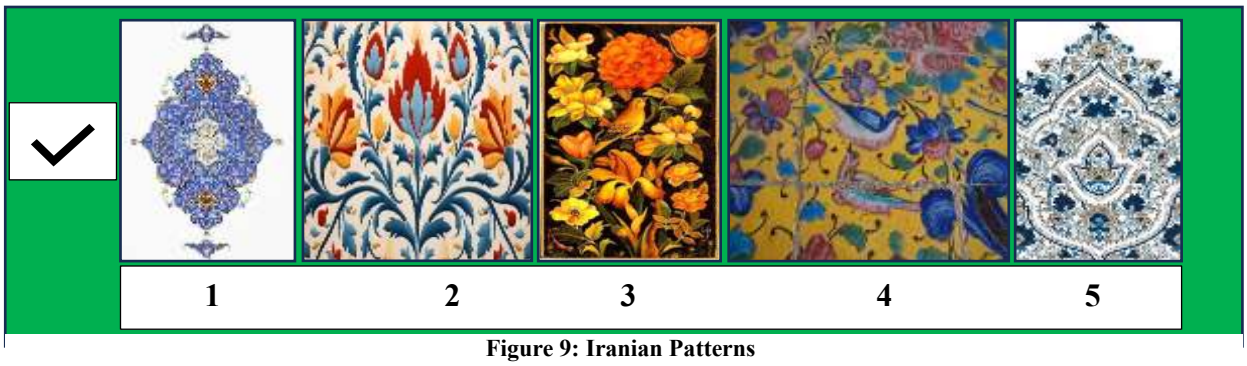


Figure 9: Iranian Patterns

1. First image — Toranj (medallion) with Islimi – Khataei composition (Tazhib illumination)
This is a Shamsa (sunburst) / Toranj (medallion) design, typical of Persian Tazhib (manuscript illumination) as well as carpet and tilework.
Definition: A highly symmetrical, almond-shaped medallion (Toranj) composed of interlacing Islimi (arabesque) and Khataei (stylized floral) motifs. Islimi refers to the abstract, curvilinear, never-ending spiral stems that symbolize infinity and divine unity. Khataei refers to the stylized blossoms, buds, and leaves derived from Chinese art (introduced in the Timurid period, 14th-15th c.).
Key features: perfect bilateral symmetry, a central rosette (Shamsa), intricate layering of spirals, rhythmic repetition, rich colors (lapis blue, turquoise, gold, coral).
Usage: frontispieces of Qur'ans and Persian manuscripts, Safavid carpet medallions, dome ceilings, and mihrabs in Isfahan mosques.
It exemplifies the Persian idea of vahdat dar kasrat — "unity in multiplicity".

2. Second image — Shah Abbasi Khataei pattern

This is the Khataei scroll, specifically the Shah Abbasi flower pattern, the dominant motif of Safavid (1501–1736) textiles, carpets, and tilework.

Definition: A continuous, rhythmic arabesque of scrolling vines bearing stylized flowers, of which the large palmette in red and blue is the Shah Abbasi flower (a stylized peony/lotus named after Shah Abbas I). Smaller blossoms, buds, and serrated leaves fill the space between the main flowers.

Key features: repetition without a clear beginning or end, curvilinear stems (Islimi) supporting naturalistic but still abstracted flowers (Khataei), balance between densely filled and open areas, flat perspective.

Usage: Isfahan carpets, Kashan silks, Qom tile panels, book borders. It was created to evoke the Islamic concept of paradise (pairi-daeza) as an eternal blooming garden.

3. Third image — Gol-o-Morgh (Flower and Bird), also called Gol-o-Bolbol

This is Gol-o-Morgh (literally "flower and bird") painting, developed especially in the Safavid period and flourishing in Zand and Qajar (18th-19th c.) lacquer, miniature, and textile art.

Definition: A naturalistic (rather than stylized) depiction of identifiable flowers — roses, irises, narcissus, chrysanthemums — together with birds, most often the nightingale (bolbol). Unlike Islimi-Khataei, the forms are not abstracted; they are delicate, shaded, and botanically recognizable.

Key features: dark background to emphasize luminous colors, free but balanced composition (not strictly symmetrical), emphasis on poetic symbolism rather than geometric order.

Meaning: The rose and nightingale symbolize the lover and the beloved in Persian mystic poetry, and more broadly the soul yearning for the divine. The garden represents jannat (paradise).

Usage: lacquer book covers and pen boxes, album margins, Qajar wall paintings, shawl embroidery, and contemporary miniature.

4. First image — Qajar Haft Rang tile with Gol o Bolbol-e Shirazi (Flower and Nightingale)

Definition: This is a hand-painted Haft Rang (seven-color) glazed tile from the Qajar period (late 18th–early 20th c.), typical of Shiraz (e.g., Nasir al-Mulk Mosque, Narenjestan-e Qavam). It depicts the Gol o Bolbol (flower and nightingale) motif, but in a popular, naturalistic style rather than the courtly Safavid abstraction.

Key features:

- Bright yellow ground (also turquoise or white in other examples), which is a signature of Shirazi Qajar tiles.

- Free, asymmetrical composition — birds and flowers are scattered naturally, not locked into strict symmetry.
- Bold black outlines and flat, unshaded colors (blue, pink, red, green, purple, brown), typical of folk Qajar art.
- The birds are stylised but recognisable, and the flowers (roses, carnations, five-petalled blossoms) are loosely botanical, influenced by 19th-century European lithographs.

Usage: Facades and interiors of Qajar houses, mosques, and bazaars in Shiraz and southern Iran.

Meaning: Same symbolism as the earlier Gol o Morgh — the nightingale (soul/lover) yearning for the rose (divine beloved, beauty). But here it is less mystical, more decorative and cheerful, reflecting the Qajar taste for color, abundance, and a break from the rigid Safavid canon.

In short: It is the Qajar, vernacular version of Gol o Morgh, made with the cheap, fast haft rang technique that allowed polychrome scenes instead of cut-tile mosaic.

5. Second image — Islimi-Khataei (Shah Abbasi) arabesque in a Mehrabi / Lachak-Toranj arrangement

Definition: This is a contemporary rendering of the classical Islimi-Khataei pattern, arranged in a pointed arch (mehrab) or medallion-and-corner (lachak-toranj) composition. It is the pattern used in Persian block-printed textiles (Ghalamkar-e Isfahan), Termeh cloth, bookbinding, and modern surface design.

Key features:

- Dense, fully symmetrical arrangement of stylised Shah Abbasi flowers (the large dark-blue palmettes) and smaller Khataei blossoms, buds, and serrated leaves, all linked by thin Islimi (spiral vine) stems.
- The pointed, layered arches recall a mihrab (prayer niche) and the lachak-toranj structure of Persian carpets — a central medallion (toranj) with corner pieces (lachak).
- Limited, muted palette (navy, beige, soft blue) — unlike the vivid Safavid or Qajar examples — making it suitable for fabric printing and contemporary interiors.
- No naturalism or birds; the design is purely abstract and rhythmic, meant to be repeated endlessly.

Historical context & usage:

- The motif originates in Safavid Isfahan (17th c.), but this crisp, graphic version is typical of Ghalamkar (hand-stamped cotton) from Isfahan and of Termeh (hand-woven silk and wool) from Yazd.

- Today it is widely used for wallpaper, digitally printed fabrics, and book covers as a “neutral” Persian ornament.

Meaning: As with all Islimi-Khataei designs, it symbolises paradise as an eternal garden — infinite growth without beginning or end, expressing vahdat dar kasrat (unity in multiplicity). The arch shape adds the idea of a gateway to paradise.

- Hillenbrand, R. (2004). Minaret: Symbol of Islam. Edinburgh University Press, pp. 234–238.
- Pope, A. U., & Ackerman, P. (1965–1967). A Survey of Persian Art from Prehistoric Times to the Present (14 vols.). Tehran: Soroush Press.
- Necipoğlu, G. (1995). The Topkapi Scroll: Geometry and Ornament in Islamic Architecture. Getty Center, Ch. 5 (Persian arabesque derivations).

Why was this pattern chosen?

Figure 10: Iranian pattern case study

Figure 11: Italian pattern

The comparative analysis of the traditional design motifs establishes an intentional framework for digital heritage reinterpretation, choosing these specific assets based on structural, historical, and contextual typologies that maximize their adaptability within contemporary spaces.

Within the Iranian patterns, Motifs 1 and 5 are selected due to their shared morphological roots, tracking back to one of the most historically significant and ancient ornamental lineages in Iranian art. Despite their intricate details, the core geometric and curvilinear structures of these two patterns exhibit high flexibility, allowing them to be systematically translated across an infinite spectrum of color palettes without losing their underlying identity or structural harmony, making them ideal candidates for parametric scaling in diverse modern environments.

In contrast, Motif 4 is chosen based on its widespread distribution across major Iranian cultural and historical landmarks, particularly in traditional tilework. Because this motif is already deeply embedded in the collective memory of traditional physical sites, it serves as an excellent operational baseline to test how a highly localized historical asset can adapt to entirely different modern architectural grids while preserving its cultural resonance.

Establishing a direct material and contextual connection with Venetian heritage, Motif 3 is selected because it echoes the dense, ornate, and deeply saturated aesthetic found in the historic decoration of Venetian gondola boats. Notably, the dark, rich background tones and organic floral compositions characteristic of these traditional Iranian motifs mirror the specific chromatic environments and decorative surfaces seen on the historic watercraft, offering a unique opportunity to explore cross-cultural dialogue through shared material and spatial palettes.

Serving as the primary point of convergence and the foundational anchor for this comparative study, Motif 2 functions as a fluid bridge between traditions. A direct visual analysis reveals a striking morphological alignment between Motif 2 and the traditional Italian—specifically Sicilian majolica—aesthetic. The two designs share a remarkably similar geometric and fluid grammar, utilizing a vibrant, high-contrast interplay of deep blues, warm yellows, and bright oranges juxtaposed against lighter backgrounds. Furthermore, the thickness, weight, and rhythmic flow of the linework are heavily aligned, as the organic, mirroring curves and central floral volutes in Motif 2 directly correspond to the repeating, symmetrically balanced botanical scrolls and cartouches flanking the central grids of the Italian majolica pattern. This profound similarity in color theory, line dynamics, and curvature highlights a shared ornamental intuition, proving that these patterns can seamlessly overlap to create cohesive, hybrid intercultural environments.

The selected case study in the location category:

Figure 10: Italy Locations(Venice)

Venice, is a city in northeastern Italy and the capital of the region of Veneto. It is built on a group of 126 islands that are separated by expanses of open water and by canals; portions of the city are linked by 472 bridges.

Why was this location chosen?

The selection of the Venice region as the primary geographical focus for this research is driven by both methodological advantages and the site's unique cultural landscape. Investigating a familiar, local territory provides a distinct scholarly advantage, allowing for deep, firsthand contextual insight and an nuanced understanding of the spatial dynamics that other regions might not readily afford.

Beyond these logistical and observational benefits, Venice represents an unparalleled artistic and historical hub, defined by a dense concentration of architectural monuments and landmark sites. As one of the world's most enduring ancient urban centers, its built environment reflects centuries of layered heritage that is ripe for contemporary digital reinterpretation. Introducing traditional patterns into this specific architectural landscape creates a compelling dialogue between historical preservation and innovation. By utilizing the Venice area, the research explores how a highly celebrated, ancient space can be thoughtfully redesigned using digital twins and parametric workflows, testing the boundaries of cross-cultural design within a site already steeped in artistic tradition.

The following examples and images are a standard, formal way to introduce visual evidence of great combination of traditional patterns and locations ,

Figure 11: Iranian Combination of Locations and Traditional Patterns

The selection of Persian Architectural Tilework is fundamental to this study’s criterion of "Computational Heritage." The mathematical precision inherent in Safavid-era tiling provides an ideal dataset for testing the transition from a physical archive to a responsive data organism. By analyzing these patterns, the research evaluates how high-resolution digital simulations can preserve both the symbolic semiotics and the structural integrity of ancient Persian craftsmanship[148].

[148] Niu, 2025, p. 12

The choice of Haft Rang is driven by the criterion of "Multi-Spectral Data Integration." This technique, characterized by tiles painted with seven distinct pigments before firing, represents a peak of Safavid architectural expression. Notable implementations at the Chehel Sotoun Palace and Ali Qapu Palace demonstrate how color is used to define spatial hierarchy and narrative depth[149]. From a Digital Twin perspective, Haft Rang serves as a case study for "Material-Aware Rendering," where the AI must account for the specific light-reflection properties of historical glazes to maintain cultural authenticity in a virtual environment[150].

The inclusion of Moarragh (Mosaic Tilework) is based on the criterion of "Granular Parametric Logic." Unlike the painted surface of Haft Rang, Moarragh consists of tiny, hand-cut tiles fitted into intricate, interlocking patterns. This technique is exemplified by the breathtaking surfaces of the Shah Mosque (Isfahan) and the Blue Mosque (Tabriz).

- **The Logic of the Part-to-Whole:** The assembly of Moarragh mirrors the "mesh-based" logic of 3D modeling, where thousands of discrete polygons form a complex surface[151].
- **Spatial Transformation:** These patterns were selected to test how AI-assisted synthesis can manage "Zellij-style" recursion. By breaking down these mosaics into their foundational geometric units, the research explores how the ancient logic of the Isfahan masters can be scaled to fit modern, large-scale public facades without losing the "narrative density" of the original work[152].

The selection of Italian patterns alongside Iranian motifs for this redesign project is strategically informed by a synthesis of cultural heritage and contextual immersion. This dual-focus approach is grounded in the theory of "Place Attachment," which posits that the most effective spatial redesigns occur when the designer possesses a deep, phenomenological understanding of the site's visual rhythm[153].

The integration of Italian motifs stems from an auto-ethnographic research methodology, facilitated by the researcher's current residency in Italy. This allows for an advanced, firsthand awareness of the

[149] Rezazadeh, 2024, pp. 115–118
[150] Manovich, 2001, pp. 215–217
[151] Niu, 2025, pp. 14–16
[152] Jouan & Hallot, 2020, pp. 7–9; Moretti, 2013, pp. 110–112
[153] Manzo & Devine-Wright, 2013, pp. 45–48

nation's aesthetic vernacular—a critical component in ensuring that digital heritage assets do not become "placeless" abstractions[154].

- **Contextual Immersion:** These patterns are deeply embedded in the urban morphology of daily life, particularly within the historic centers of Southern Italy and the Amalfi Coast. By observing these motifs in their natural architectural environment, the project seeks to translate the lived experience of the city's visual rhythm into a formal design framework.
- **Reframing the Archive:** According to Manovich[155], the digitization of a "lived" space requires the researcher to act as a bridge between the physical atmosphere and the digital data organism. This firsthand observation ensures that the resulting Digital Twin captures the subtle interplay between light, materiality, and the historic urban fabric that defines Mediterranean identity[156].

By synthesizing the "insider" perspective of Italian urbanism with the structural complexity of Iranian heritage, the research evaluates how intercultural design can foster a sense of "belonging" in globalized spaces, preventing the technological alienation often associated with large-scale digital interventions[157].

The inclusion of Iranian motifs serves as a vital exploration of cultural identity and inherited knowledge. Drawing from an innate understanding of Persian symbolism and the historical narratives embedded within these designs, this project utilizes patterns observed across diverse architectural sites in Iran. The vivid polychromatic nature of these Persian geometries offers a unique aesthetic synergy with the atmospheric and scenic complexity of Venice. By transposing these intricate patterns onto the Venetian urban fabric, the redesign aims to facilitate a cross-cultural dialogue that enhances the visual heritage of both traditions, leveraging their shared emphasis on ornamental detail and vibrant public spaces.

"Why was this specific geographic and architectural location selected as the primary laboratory for testing the spatial adaptability of the Digital Twin?"

Venice is selected as the focal site for redesign and the incorporation of traditional patterns because the researcher resides within its urban fabric and possesses an intimate, first-hand understanding of its spatial texture, material details, and contextual nuances. This selection is grounded in the theory

[154] Niu, 2025, pp. 12–14
[155] 2001, pp. 218–220
[156] Jouan & Hallot, 2020, pp. 7–9
[157] Niu, 2025, pp. 62–65

of "Place Attachment," which argues that an authentic redesign of space requires a deep, phenomenological connection to the site's historical and visual rhythm[158].

This localized expertise enables a more precise, nuanced, and analytically rigorous approach than would be attainable through the selection of an alternative, less familiar city. By acting as a "Participant-Observer," the researcher can translate the subtle interplay of light, water, and Istrian stone into the digital data model—a process Manovich [159]describes as bridging the gap between the "physical atmosphere" and the "digital data organism."

Furthermore, the selection of Venice serves as a critical laboratory for testing "Structural Interoperability." The city's unique architectural morphology provides a complex environment to evaluate how digitized heritage assets, such as Persian or Polish motifs, can be integrated into a sensitive, "high-density" historical context without causing "technological alienation[160]".

Venice is selected as the primary site for redesign and the integration of traditional patterns due to the researcher's sustained residency and consequent in situ expertise in the city's urban texture, material palettes, and socio-spatial nuances. This localized knowledge facilitates a methodologically rigorous approach, enabling precise identification, contextual interpretation, and sensitive application of traditional design elements—advantages unattainable through selection of a less familiar urban context. To substantiate the viability and aesthetic coherence of such interventions, visual documentation of exemplary locations where traditional patterns are comprehensively and successfully integrated into contemporary design will be provided. These case studies serve as empirical references, demonstrating the feasibility of harmonizing heritage motifs with modern urban requirements while informing the specific design strategies proposed for Venice.

3.2. Data Collection

The data employed in this research comprises both primary and secondary sources. Data validation was conducted through cross-referencing information obtained from the official websites of UNESCO and the Iranian Encyclopaedia Islamica Center.

3.2.1.Primary Data

The primary empirical data consists of original photographic documentation compiled during fieldwork, focusing on material culture, artisanal heritage, and vernacular architecture within the Venetian lagoon.

[158] Manzo & Devine-Wright, 2013, pp. 45–48
[159] 2001, pp. 218–220
[160] Niu, 2025, pp. 62–65; Jouan & Hallot, 2020, pp. 7–9

- **Venetian Material Culture and Materiality:** Original photography captures key objects of traditional Venetian craftsmanship, specifically gondolas and Carnival masks (Figure 29).

*Primary data ⟶ the photos of Gondola boats and Carnival Masks, which were taken by me

Figure 12: Photos of Italian traditional tools, taken by me

Carnival Masks: Central to historical Venetian civic life, these artifacts historically functioned to suspend rigid socioeconomic hierarchies and individual identities during festivities. Characterized by intricate ornamental patterns and complex materiality, they represent a distinct nexus of historical craft, cultural symbolism, and artistic expression.

Gondola Boats: These traditional rowing vessels represent a highly specialized form of maritime engineering optimized for navigating the shallow, micro-tidal environment of the Venetian canals. Balancing functional hydrodynamics with refined artisanal woodworking, the gondola stands as an enduring cultural symbol of Venice, embodying centuries of localized maritime heritage and ornamental tradition.

Figure 13: Venice- Burano

*Primary data: ⟶ the photos of Burano Island, which were taken by me

Burano is a small island located in the Venetian Lagoon. Today, it is renowned for its vividly painted houses and its enduring tradition of lace-making. The practice of painting houses in bright colors dates back several centuries and remains a defining feature of the island. These colors are strictly regulated by the local government, ensuring the preservation of Burano's distinctive and characteristically vibrant appearance.

3.2.2.Secondary Data

*Secondary ⟶ the photos of motifs and traditional patterns

The secondary dataset is comprised of historical visual documentation, architectural schematics, and archival records concerning traditional decorative motifs and geometric patterns (Figures 31 and 32). These resources were sourced from authoritative cultural heritage platforms:

Link 1: Iran (Islamic Republic of) - UNESCO Intangible Cultural Heritage

Link 2: www.cgie.org.ir

Figure 14: Iranian traditional patterns

*Secondary ⟶ the photos of motifs and traditional patterns

Data sources links:

Link 1: Iran (Islamic Republic of) - UNESCO Intangible Cultural Heritage

Link 2: www.cgie.org.ir

They are rooted in a long-standing tradition of decorative arts that privileges geometric structure, symmetry, and stylized vegetal motifs. Commonly encountered in tilework, manuscripts, textiles, and architectural ornamentation, these patterns articulate philosophical concepts of harmony, infinity, and order through intricate repetition and carefully balanced compositions.

Figure 15: Iranian traditional patterns

These patterns derive from a long-established tradition of decorative arts distinguished by geometric rigor, formal symmetry, and stylized vegetal motifs. Widely employed across media such as tilework, illuminated manuscripts, textiles, and architectural ornamentation, they embody philosophical concepts of harmony, infinity, and order. These principles are articulated through systematic repetition, proportional balance, and carefully structured compositional frameworks.

First Step: 2D Modeling

The 2D models are inserted here, which are a combination of the chosen locations and patterns. They are hand-drawn on canvas with acrylic.

3.3. Prototype development

This is one building, according to the structures that are living in Venice, this picture is generated by AI, I just wanted to have a simple basic area that can be redesign with traditional patterns, looking at the walls and scales which can be designed and shape of them is important to know how, what and which abilities and possibilities we have to edit and then redesign the area.

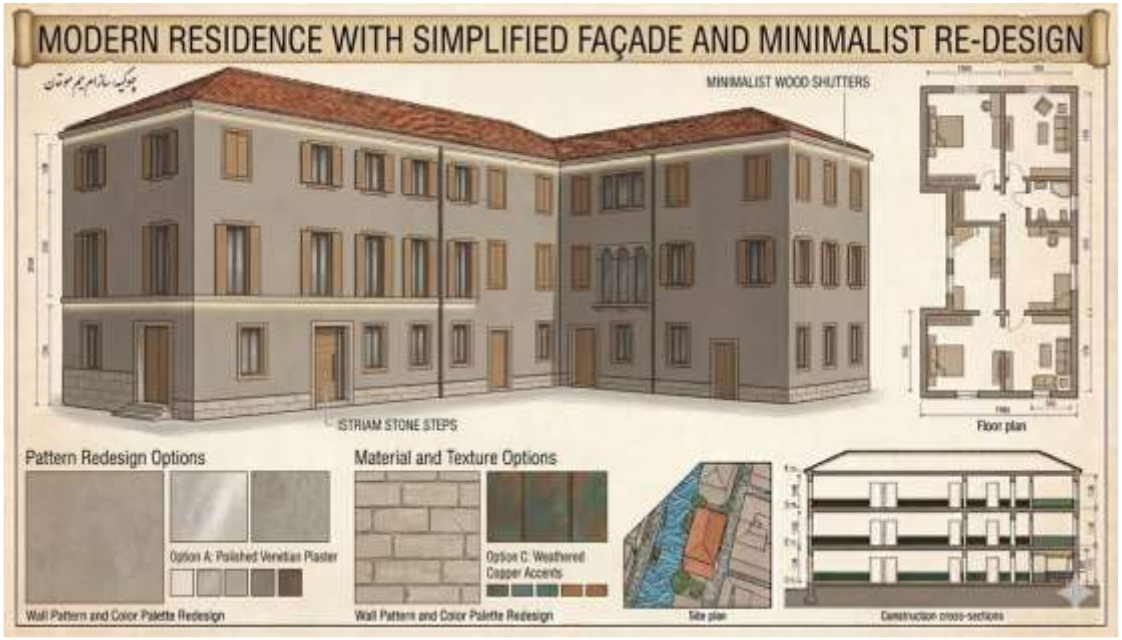


Figure 16: AI suggestion about Location case study Prompt: Architectural presentation sheet, modern residence minimalist redesign, isometric view plus floor plans and sections, material samples including Istrian stone and Venetian plaster, vintage technical drawing style on cream paper, annotated with dimensions, muted color palette, professional architectural layout --ar 3:2 --style raw

According to the first phase of the methodology, the selected areas were first delineated on the canvas and subsequently integrated with the chosen traditional patterns. The integration of patterned elements within the designated zone serves as a conceptual rendering to illustrate the final appearance of the proposed redesign. The primary transformation is aesthetic in nature, with the exterior walls and surrounding surfaces functioning as the principal canvas for spatial and visual reconfiguration. This process resulted in alignment with the objectives of the research:

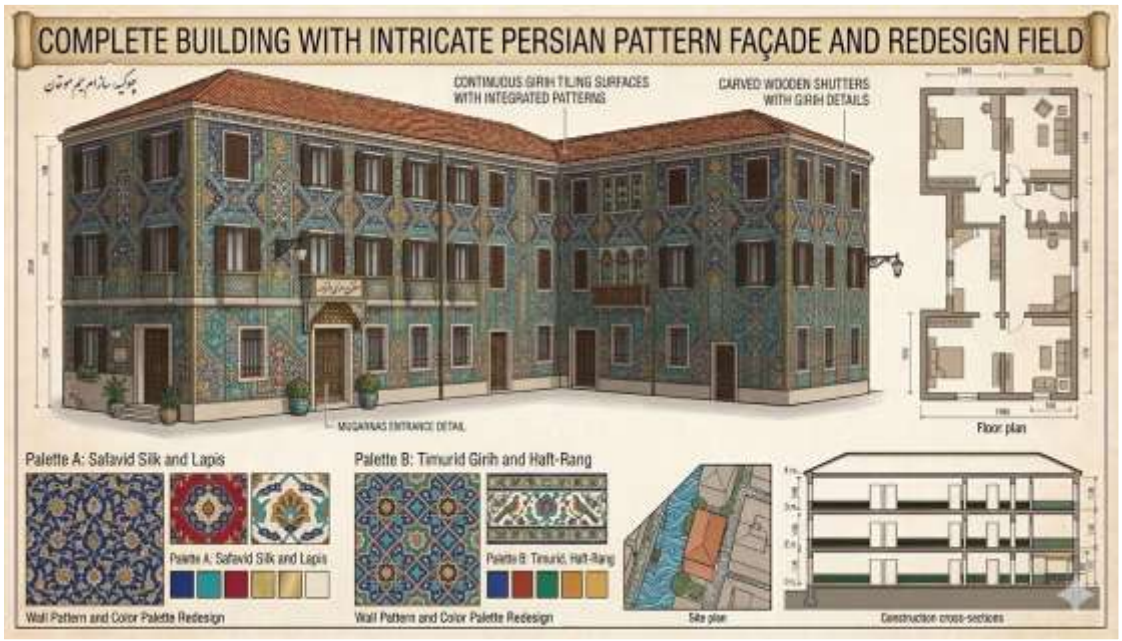


Figure 17: AI suggestion about the Location and Patterns case study, Prompt: Architectural presentation sheet, traditional building with intricate Persian Girih tile patterns covering façade, Muqarnas entrance, carved wooden shutters, isometric view plus floor plans and sections, material palettes showing Safavid Silk/Lapis and Timurid patterns with color chips, vintage technical drawing on cream paper, annotations in English and Persian calligraphy, turquoise and terracotta color scheme --ar 3:2 --stylize 250

3.4. Pattern–space integration

During a research internship at the University of Bologna under the supervision of Professor Marilena Daquino, we investigated visual problem-solving methodologies within digital library interfaces. The primary outcome of this research was the implementation of structured data identity cards (or metadata profiles) designed to systematically display critical information, such as artist names, geographical locations, and associated historical contexts. Building upon this framework, the present study aims to adapt and extend this visual methodology, applying it to a distinct corpus of content aligned with the core objectives of this thesis.

This section provides a comparative analysis of the original physical conditions and their digitally reconfigured models. Each redesign integrates distinct regional motifs and ornamental patterns, which are explicitly identified and contextualized herein to demonstrate the methodological framework underlying these spatial and aesthetic transformations.

The proposed model utilizes a centralized Toranj (medallion) motif, characterized by an Islimi-Khataei vegetal composition, as the primary decorative program for the interior flooring. Conversely, the vessel's exterior surface is articulated through Qajar-era 'Haft Rang' (seven-colored) tilework, featuring the distinct Gol-o-Bolbol-e Shirazi (Rose and Nightingale) iconographic tradition.

Figure 20: *Shah Abbasi Khataei* pattern

+

Figure 18: Qajar *Haft Rang* tile with *Gol o Bolbol-e Shirazi*

+

Figure 19: Venice - Burano

These represent AI-generated prototypes proposed for the redesign of floor plans and building-scale configurations.

Buildings

Figure 22: AI Venice Redesign (Buildings)

Photorealistic view of a Venice canal lined with colorful Burano-style houses, traditional Venetian architecture with boats docked along the water, building facades integrated with Qajar-era Haft Rang tilework featuring Gol-o-Bolbol-e Shirazi (Rose and Nightingale) iconography — intricate floral patterns in cobalt blue, turquoise, and crimson on ochre backgrounds, carved wooden shutters with Persian motifs, sunny Mediterranean lighting, clear blue sky, canal reflection, architectural photography style, highly detailed, 8k, realistic textures of aged plaster and ceramic tiles

Floor

Figure 21: AI Venice Redesign (Floor)

Aerial perspective looking down a Venice canal, the canal floor/pavement completely covered with an elaborate Persian carpet design featuring Toranj medallion motif and Islimi-Khataei vegetal composition, Gol-o-Bolbol-e Shirazi pattern with stylized roses and nightingales, vibrant yellow-gold base with navy blue and crimson floral details, colorful Burano buildings lining both sides of the canal, boats floating on the patterned surface, sunny day, photorealistic architectural visualization, sharp focus, vibrant colors, 8k resolution

Almost Half of the artwork is done here:

Figure 24: Middle levels of modeling(Venice- Floor)

First steps of drawing: 2D Prototype:

Basic Selected Location

Basic Traditional Patterns

Basic Traditional Patterns

Figure 23: : first levels of modeling (Venice- Floor)

Given the distinctive architectural typologies and chromatic characteristics of the residential structures in the selected study area, the redesign intervention was deliberately focused on floor-plan reconfiguration rather than building-scale modifications. Nevertheless, the underlying methodology remains fully transferable and can be readily adapted to alternative case studies or architectural contexts.

Following the presentation of the foundational linear schematic and intermediate modeling stages, I will examine selectively modified components that were redesigned through the integration of traditional pattern systems. These adapted elements function as generative archetypes, establishing the foundational reference framework for the broader model:

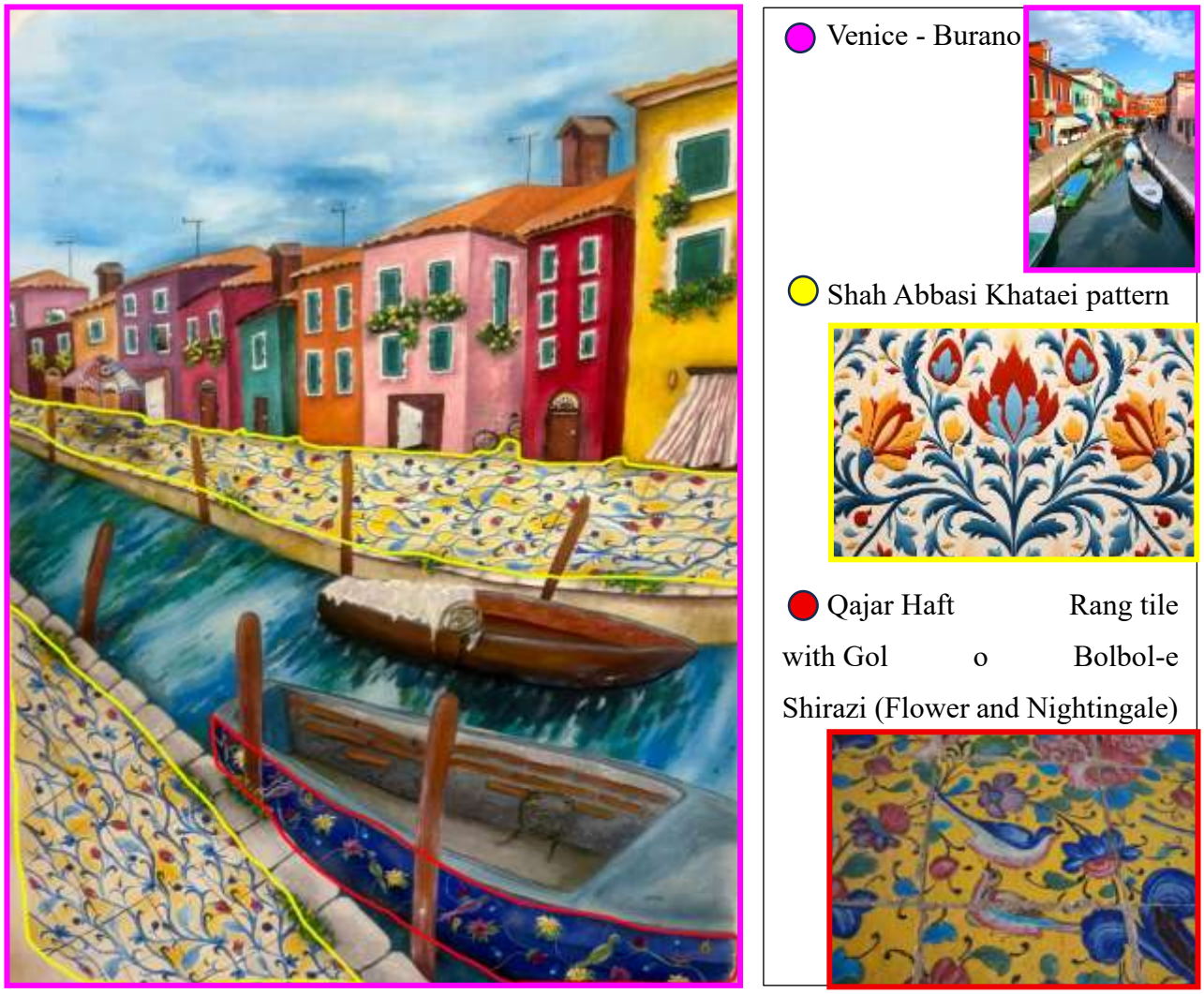


Figure 25: First Modeling Calibration and its identity card

Figure 26: Second Modeling Calibration and its identity card

3.4. Iterative Refinement

According to the second phase of the methodology, the selected tools were first delineated on the canvas and subsequently integrated with the chosen traditional patterns. This process resulted that align with the objectives of the research. At some points, there are other elements like clothes, traditional music equipment, and so on, which could help as factors to have a better combination that can make more sense about the project's aim:

Almost Half of the artwork is done here:

Figure 27: Middle levels of modeling(Venice – Gondola Boat)

Figure 28:First Modeling Reliability and it's identity card

Venice

Gol-o-Morgh (Flower and Bird)

Tar, Iranian Musical Instrument

Carnival Mask

Iranian Traditional Cloth

Carnival Masks were selected as the focal subject due to their strong tourist appeal, widespread popularity, and status as one of the most visually prominent and recognizable elements within the study area.

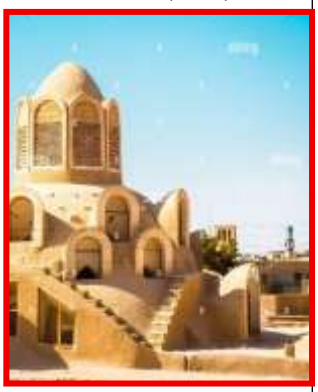
Almost Half of the artwork is done here:

Figure 29: Middle levels of modeling(Carnival Masks)

Figure 30: Second Modeling Reliability and it's identity card

Carnival Mask

Yazd TGraditional Architectural area(Iran)



Gol-o-Morgh (Flower and Bird)

Iranian Green Fabric with golden pattern

3.5.Final Step:3D Modeling

Digital Twin or Blender software is used to create the final model.

This project reinterprets and adaptively applies traditional design patterns as tangible expressions of cultural identity and heritage, countering their erosion amid homogenizing modern development. By integrating these patterns into contemporary contexts, the project optimizes both aesthetic resonance and functional efficacy while safeguarding intangible cultural significance—thereby establishing a critical dialogue between historical continuity and present-day urban imperatives.

For2D Designs:

1. Demonstrating a well-executed and innovative compositional combination.
2. Presenting a visually rich and chromatically dynamic scene.
3. Achieving enhanced impact as a result of the new design approach.
4. Facilitating cross-cultural understanding and familiarity through visual representation.

Conceptual Flow(Bridding past and present):

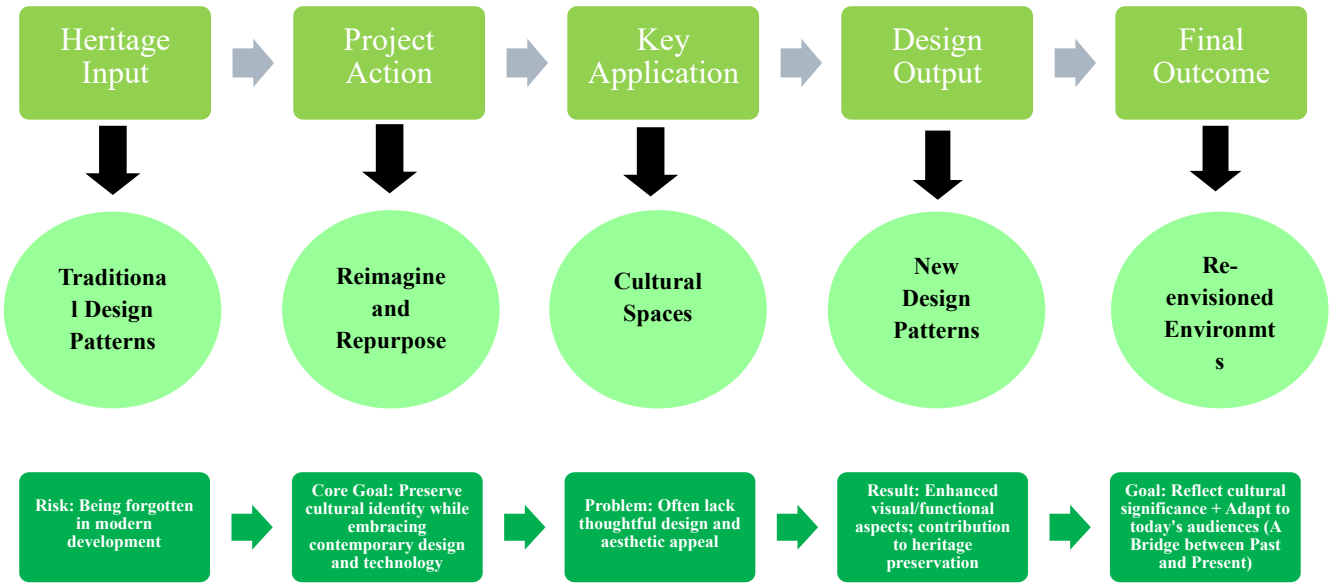


Figure 31: Result Chart

4. Result and Discussion:

1. The qualitative research approach results in the creation of final two-dimensional models or prototypes produced through manual, hand-drawn techniques.

***The core of this research utilizes a qualitative methodology centered on the production of physical, two-dimensional prototypes. Eschewing digital automation, the project prioritizes manual, hand-drawn techniques to ensure a tactile connection between the researcher and the medium. This artisanal approach allows for a nuanced exploration of line weights, symmetry, and geometric precision that mimics the historical craftsmanship inherent in both Italian and Persian traditions. By generating these prototypes manually, the research captures the "human error" and organic flow that characterize traditional architectural ornamentation.

2. The selected examples serve as analytical and exploratory case studies within a descriptive–explanatory framework and are organized into two main categories.

** This study adopts a descriptive-explanatory framework, utilizing selected architectural sites as primary case studies for pattern application. These examples are not merely decorative subjects but serve as analytical environments where the compatibility of diverse cultural motifs is tested. The research is bifurcated into two distinct categories: Category A focuses on the indigenous Italian vernacular, while Category B introduces the imported Persian geometric systems. This organizational structure allows for a comparative analysis of how different cultural "languages" respond to the same spatial constraints.

3. The findings demonstrate enhanced visual and conceptual impact through the application of an innovative design approach, while fostering cross-cultural awareness via visual expression.

** The results of this study indicate that the integration of non-native patterns into a localized architectural context significantly heightens both the visual dynamism and the conceptual depth of the site. By applying an innovative redesign approach—transposing Middle Eastern geometries onto Mediterranean forms—the work transcends mere decoration. It acts as a vehicle for cross-cultural awareness, demonstrating that visual expression can serve as a bridge between disparate geographies, fostering a globalized architectural aesthetic that respects individual cultural legacies.

4. The research outputs comprise two-dimensional models that combine selected spatial settings with traditional patterns, executed manually on canvas using acrylic materials.

** The tangible outputs of this research are high-fidelity, two-dimensional models that synthesize specific spatial settings with intricate traditional motifs. The execution is grounded in traditional

materiality, utilizing canvas as the substrate and acrylic pigments as the primary medium. The choice of acrylics allows for a layering of color and opacity that reflects the vibrant tiles of Iran and the sun-drenched plaster of Italy. This fusion of architectural drawing and fine-art painting creates a hybrid representation that highlights the "precious" interiority of the chosen Venetian and Southern Italian locations.

5. The study's originality lies in its integrated methodology, which connects traditional decorative patterns with specific geographic and cultural contexts.

** The scholarly contribution of this study is found in its integrated methodology, which establishes a direct semiotic link between traditional decorative patterns and their specific geographic-cultural environments. While many studies treat ornamentation as an isolated element, this research argues that patterns are inextricable from the "spirit of place" (genius loci). The originality of the work lies in the purposeful collision of two distinct cultural histories—Italian and Persian—to create a new, synthesized design language that addresses contemporary needs for cultural inclusivity in architecture

Conclusion and Future Directions:

This research successfully establishes a methodology for bridging the gap between historical heritage and contemporary design, ensuring that traditional decorative patterns—which are in danger of being completely forgotten—can be actively revived and reused. By utilizing a dual approach that spans from tactile, material two-dimensional prototyping to dynamic, immersive Digital Twins, this framework moves ancient motifs out of static archives and into the living fabric of modern life. Whether applied to the redesign of private interiors or public environments, this workflow demonstrates that traditional art can serve as a functional, structural foundation for contemporary spaces, preventing the erasure of fragile cultural legacies.

Looking ahead, a promising future direction for this work lies in the purposeful cross-pollination and combining of different cultural pattern systems. Mixing and synthesizing diverse geometric systems and cultural traditions can generate entirely new design languages tailored to our globalized world. However, a critical boundary must be maintained in future implementations: even when blending and hybridizing these visual systems, designers must pay rigorous attention to keeping the core historical identity and integrity of the original motifs alive. Innovation should never come at the cost of cultural erasure. Furthermore, for these tech-driven and cross-cultural interventions to succeed long-term, deep attention must be paid to how they are received by the public. These redesigned environments must achieve widespread social acceptance, ensuring they remain deeply accessible, meaningful, and emotionally engaging for people across all generations, backgrounds, and communities.

Finally, the significance of this project extends far beyond the specific regions studied here. The integrated methodology developed in this thesis—combining manual craftsmanship, computational 3D modeling, and spatial theory—is highly scalable and adaptable. It can be seamlessly applied to entirely different architectural locations, diverse geographic contexts, and various other endangered design traditions worldwide, offering a universal blueprint for the preservation and creative revival of global cultural heritage.

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LIST OF ABBREVIATIONS

1. AI: Artificial Intelligence
2. AR: Augmented Reality
3. BACODI: Knowledge Base name (not expanded in text)
4. BIM: Building Information Modeling
5. BMW: Bayerische Motoren Werke (BMW Group)
6. CAD: Computer-Aided Design
7. CGIE: Iranian Encyclopaedia Islamica Center
8. CNR: Consiglio Nazionale delle Ricerche (Italian National Research Council)
9. CNRS: Centre National de la Recherche Scientifique (French National Centre for Scientific Research)
10. CT: Computed Tomography
11. DPH: Digital and Public Humanities
12. DH: Digital Humanities
13. DT: Digital Twin
14. DTNs: Digital Twin Networks
15. FAIR: Findability, Accessibility, Interoperability, and Reusability
16. GANs: Generative Adversarial Networks
17. GIS: Geographic Information Systems
18. GLAM: Galleries, Libraries, Archives, and Museums
19. GPT: Generative Pre-trained Transformer
20. HiCO: Historical Context Ontology
21. ICON: Formal Ontology name (not expanded as an acronym in text)
22. IUAV: Università Iuav di Venezia
23. IoT: Internet of Things

24. LLMs: Large Language Models
25. LiDAR: Light Detection and Ranging
26. LIS: Library and Information Science
27. LOD: Linked Open Data
28. MiC: Ministero della Cultura (Italian Ministry of Culture)
29. MIT: Massachusetts Institute of Technology
30. MoMA: Museum of Modern Art
31. MRI: Magnetic Resonance Imaging
32. NLP: Natural Language Processing
33. NYU: New York University
34. ODI: Ontologia dei Destini Incrociati
35. OCDM: OpenCitations Data Model
36. OTA: Over-the-air
37. OWL 2 DL: Web Ontology Language 2, Description Logic profile
38. PROV-O: Provenance Ontology
39. PNRR: Piano Nazionale di Ripresa e Resilienza (Italy's National Recovery and Resilience Plan)
40. RDF: Resource Description Framework
41. RDF-star: RDF* (W3C-related RDF extension/feature set)
42. SemLib: Semantic Library Project/Framework name (not expanded in text)
43. SPARQL: SPARQL Protocol and RDF Query Language
44. SPICE: Social Cohesion, Participation, and Inclusion through Cultural Engagement
45. TU: Technische Universität / University of Technology
46. UNESCO: United Nations Educational, Scientific and Cultural Organization
47. UX: User Experience

48. VeDPH: Venice Centre for Digital and Public Humanities

49. VR: Virtual Reality

50. W3C: World Wide Web Consortium

51. XRF: X-ray Fluorescence

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