

A Hybrid Deep Learning Framework for the AI-Assisted Design of Culturally Sustainable Sculptures

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ABSTRACT

The integration of Artificial Intelligence (AI) into creative and cultural fields marks a significant technological shift, offering new ways to enhance creativity by combining traditional techniques with data-driven insights. This study addresses a specific need in Jeddah, Saudi Arabia, to harmonize urban development with cultural preservation, a key objective of Saudi Arabia's Vision 2030. It highlights a research gap at the intersection of AI and cultural sustainability, particularly in the design of public art that reflects local identity. To address this issue, the paper introduced a new four-phase hybrid deep learning framework for the AI-assisted design of culturally sustainable sculptures. The approach involves building a curated dataset of Jeddah's cultural aesthetics, using unsupervised learning to group artistic styles and supervised learning to assess public sentiment. These insights are integrated into a practical AI tool for artists. The framework's effectiveness was illustrated through a case study on the Jeddah Corniche, where it helped guide the iterative design of a sculpture, increasing its predicted public approval from 62% to 89%. This work introduces a new AI model for cultural style and sentiment analysis, providing a scalable, evidence-based approach to foster cultural sustainability in urban development through technology.

Keywords-artificial intelligence; deep learning; Saudi cultural; sculptures; cultural sustainability

I. INTRODUCTION

AI integration into creative and cultural fields marks a significant technological advance. AI's ability to analyze data, recognize patterns, and generate insights is being explored in various domains, including art and design [1]. This shift introduces new methods for enhancing creativity, blending traditional techniques with data-driven decisions and innovative tools for artists and urban area planners [2].

In Jeddah, Saudi Arabia, there is a growing need to align urban development with cultural preservation, a key goal of Saudi Vision 2030 [3]. The city's cultural heritage and modern landscape offer a rich tapestry for exploration. However, creating public art that resonates with local identity and is well-received remains a complex task, requiring a delicate balance between innovation and tradition [4].

Earlier studies have tackled this issue from different angles. Researchers in cultural and urban fields have thoroughly explored Saudi Arabia's heritage and the social significance of public spaces. Meanwhile, other studies have concentrated on using AI in creative fields, education, and optimizing technical design. However, there is a noticeable gap where these fields intersect; currently, no research provides a practical, AI-based

approach for promoting cultural sustainability through public art sculptures in Jeddah [5].

Thus, this study aimed to bridge the identified research gap by proposing a novel, four-phase deep-learning framework, called the Hybrid Deep Learning Framework for AI-Assisted Design of Culturally Sustainable Sculptures in Jeddah. The primary goal is to develop a practical, evidence-based model that assists in the design of public sculptures that are both culturally resonant and publicly appealing. The process is designed to analyze Jeddah's cultural aesthetics, cluster artistic styles, predict public sentiment, and synthesize these insights into an actionable tool for artists, thereby facilitating a culturally informed and iterative design process.

The contribution of this work is twofold. First, it introduces a new AI model that effectively combines unsupervised learning for cultural style clustering with supervised learning for public sentiment prediction and an innovative hybrid approach not previously used in this context. Second, it offers a practical and scalable solution for urban development, as demonstrated through a case study on the Jeddah Corniche, which shows how AI can enhance design outcomes, as evidenced by an increase in the predicted public reception of a sculpture from 62% to 89%. This research presents a new paradigm for promoting cultural sustainability technology.

II. RELATED WORK

A significant number of studies have focused on cultural preservation, vernacular architecture, and the socio-cultural dynamics of spaces in the Saudi context, particularly in cities such as Makkah, Diriyah, and Jeddah. These works provided valuable documentation, theoretical frameworks, and insights into cultural heritage, identity, and urban social behavior. Research has explored the preservation of culture, traditional architecture, and the social dynamics of Saudi Arabian cities, especially in Makkah, Diriyah, and Jeddah. These studies have

offered valuable documentation, theoretical frameworks, and insightful analyses of cultural heritage, identity, and urban social behavior. However, they often relied on single case studies or focused on specific historical periods, which limited their widespread applicability. Furthermore, these studies rarely incorporated AI or technological applications. They concentrated, instead, on traditional art forms, historical discussions, and teaching methods that may be outdated in the context of modern technology research. Table I presents the importance and limitations of the existing studies.

TABLE I. RELATED WORKS WITH THEIR IMPORTANCE AND DRAWBACKS

| Ref | Importance | Limitations | AI/sustainability focus |
|------|--|--|-------------------------|
| [3] | This study discussed strategic urban sustainability planning aligned with Saudi Arabia's Vision 2030. It provided a high-level, policy-oriented framework. | This study did not specify the role of technologies, such as AI, within its planning framework. It remained broad and strategic. | ✓ |
| [5] | It connected the philosophy of place and time to modern design principles. It developed a culturally grounded theoretical approach. | It did not provide broad practical applications. It offered a theoretical examination based on a single case study of Diriyah. | × |
| [6] | This study highlighted the cultural and spiritual aspects of preservation. It emphasized the importance of sustainability in this context. | It did not provide a high degree of generalizability. It offered a case study focused specifically on Makkah ornaments. | × |
| [7] | This study focused on the practical aspects of interior design for cultural exchange. It offered a straightforward methodological approach. | The study did not expand into a broader architectural or urban design scope. Its findings were limited to arts and crafts centers. | × |
| [8] | This study offered a detailed architectural analysis of a significant modern cultural building. It developed a deep understanding of a single architectural case. | It did not undergo widespread peer review, as it was a thesis. It did not provide an analysis beyond a single building. | × |
| [9] | It introduced valuable documentation on essential vernacular architecture. It offered important insights into cultural heritage. | Instead of in-depth analysis, this study provided descriptive analysis, focusing on past values rather than current ones. | × |
| [10] | A study examining human behavior in public spaces in Jeddah was conducted. It offered valuable insights into urban social dynamics. | Significant changes in the urban context have occurred since the publication of the study in 2015, which were not considered in this study. Current conditions may not be reflected in its findings. | × |
| [11] | This study examined the pivotal role in shaping society and cultural development. It highlighted a crucial element of the cultural landscape. | Neither primary data nor secondary data were analyzed in this study. Discussions are likely focused on theory or policy. | × |
| [12] | An empirical study was conducted in a key Saudi city on the social function of open spaces. The research was based on direct observation or data collection. | This study provided valuable insights but requires further investigation and refinement. | × |
| [13] | This study proposes a cultural model of national development. A new growth framework was introduced. | It did not include the implementation or validation of the model. Although there was no practical testing, the proposal stayed conceptual. | × |
| [14] | It provided empirical, solution-oriented research for improving urban sustainability. It offered practical approaches to a key challenge. | This study did not produce findings that apply universally to all public spaces. It focused on a single case study park. | ✓ |
| [15] | This study reviewed the novel topic of HRI in a high-relevance context, such as KSA. It synthesized existing work on a specific emerging field. | This study did not present new primary research. It offered synthesis rather than original data. | ✓ |
| [16] | This study provided a deep, expert analysis of a significant artist's work and influence. It offered valuable insights into an individual's contribution. | This study did not provide broader applicability beyond the focus on a single artist. Its conclusions were limited in scope. | × |
| [17] | This study provided a foundational discussion on the role of AI in creativity, as presented by leading experts. It introduced key theoretical concepts that are foundational to the field. | It did not include practical applications or case studies. It remained a conceptual/theoretical exploration. | ✓ |
| [18] | This study established a valuable cross-disciplinary framework between HCI and art. It proposed a bridge between these fields. | It did not provide a context specific to Saudi Arabia or the Gulf region. It offered a broader theoretical perspective. | × |
| [19] | This study analyzed local narratives and identity, which are crucial for understanding the cultural context. It provided essential background for design. | It did not focus on physical design or the application of AI. It was centered on historical discourse and writings. | × |
| [20] | This study directly addressed the use of AI (Text-to-Image) in pedagogy with practical implications. It offered an applicable framework for education. | This study did not focus on professional practice or broader design applications. Its scope was specifically educational. | ✓ |

| | | | |
|------|--|---|---|
| [21] | This study explored practical ML applications across art and design disciplines. It indicated concrete uses for the technology. | This study did not delve deeply into specific technical details, offering an overview rather than a deep analysis. | ✓ |
| [22] | This study combined AI-HMI with the practical design domain of interior design. It proposed a direct application of technology to the field. | This study did not deeply address the cultural aspects of design. It had a technical focus that may have overlooked socio-cultural factors. | ✓ |
| [23] | This study presents a seminal and comprehensive book on AI in creativity by a leading author. It offered a broad overview of the field. | This study was not specific to the Saudi, architectural, or Islamic art contexts; its perspective was general. | ✓ |
| [24] | This review article synthesized the current state of AI in the arts. It provided a summary of existing knowledge and trends. | This study did not present new primary data or original case studies. It compiled and analyzed existing research. | ✓ |
| [25] | This study explored the timely topic of human-AI collaboration in creative processes. It addressed a relevant and emerging field of study. | This study highlighted famous AI-generated works, such as artworks sold at auctions. The study focused on successful examples and overlooked failed or less impressive AI projects. | ✓ |
| [26] | This study presented an educational model for urban knowledge development in Jeddah. It proposed a framework for learning. | This study did not focus on technology and may be dated, as it was published in 2011. Its relevance to current tech trends may be limited. | × |
| [27] | This study documented and advocated for the role of urban art in the placemaking process. It highlighted the importance of public art. | This study did not focus on digital technology or the application of AI. It dealt with physical and traditional art forms. | × |
| [28] | This study examined the social impact of a recent significant cultural event, the Islamic Arts Biennale. It provided insights into large-scale cultural programming. | This study did not cover the longer-term or technological aspects of the event's impact. It was a case study on a single occurrence. | × |
| [29] | This study focused on modernizing traditional arts to preserve cultural identity. It offered a strategy for cultural sustainability. | This study did not include recent technological advancements, such as AI, as it was conducted in 2015. Its technological perspective may be outdated. | × |
| [30] | This study explored new directions for Saudi art through the medium of installations. It proposed contemporary avenues for artistic expression. | This study did not emphasize digital art forms, focusing instead on traditional ones. | × |
| [31] | This study applied AI directly to a core architectural challenge of designing tall buildings. It developed a technical solution for optimization. | This study did not focus on cultural or artistic aspects of design. It was highly technical, dealing with structural optimization. | ✓ |
| [32] | This study emphasizes creativity, technology, and sustainability in Jeddah. It offered a variety of perspectives on these themes. | This study focused on a single region and did not include different solutions or viewpoints from other countries. | ✓ |
| [33] | This study provided a practical application of AI to address the significant logistical and sustainability challenges of managing the Hajj. It offered a real-world solution. | This study did not focus on the cultural or artistic design elements of the event. Its application was for crowd management and logistics. | ✓ |
| [34] | This study provided valuable empirical data on the perspectives of architects and clients regarding AI adoption in KSA. It offered insights into market readiness and attitudes. | This study did not focus on the technical or artistic output of AI systems. It examined adoption preferences rather than creative applications. | ✓ |

III. METHODOLOGY

The proposed methodology is designed to bridge the gap between the Saudi cultural context and modern AI tools. It employs a multi-stage, hybrid deep-learning pipeline to analyze, interpret, and generate insights for the creation of culturally resonant artistic sculptures in Jeddah. The process can be broken down into four primary phases: data acquisition and processing, data preprocessing and feature extraction, model development and training, and implementation and design synthesis. Figure 1 illustrates the developed hybrid deep learning framework used in the study. The process begins with the creation of a novel, curated dataset specific to Jeddah's context. The data are then preprocessed and transformed into meaningful numerical features using a pre-trained Convolutional Neural Network (CNN).

- Phase 1: Data acquisition and processing - This initial phase focuses on creating a comprehensive, multimodal dataset specifically tailored to Jeddah's distinctive cultural and urban environment. It encompasses the collection of data

from various sources, such as digital archives of cultural heritage, images of the local cityscape, and existing art, as well as content contributed by the public. A crucial component of this phase involves sentiment labeling through public surveys, wherein community feedback was obtained and utilized to annotate the data, thereby reflecting public preferences and emotional significance.

Phase 2: Data preprocessing and feature extraction: the raw visual data from Phase 1 are prepared and transformed into a format suitable for AI analysis. This phase started with preprocessing the images, which involves tasks, such as resizing to a consistent size, normalizing pixel values, and increasing the dataset's diversity to enhance model robustness. Next, a pre-trained CNN on a large dataset to identify and extract high-level, meaningful features, such as shapes, textures, and patterns, from the Jeddah images. These features were then converted into numerical representations that encapsulate the visual and stylistic characteristics of the images.

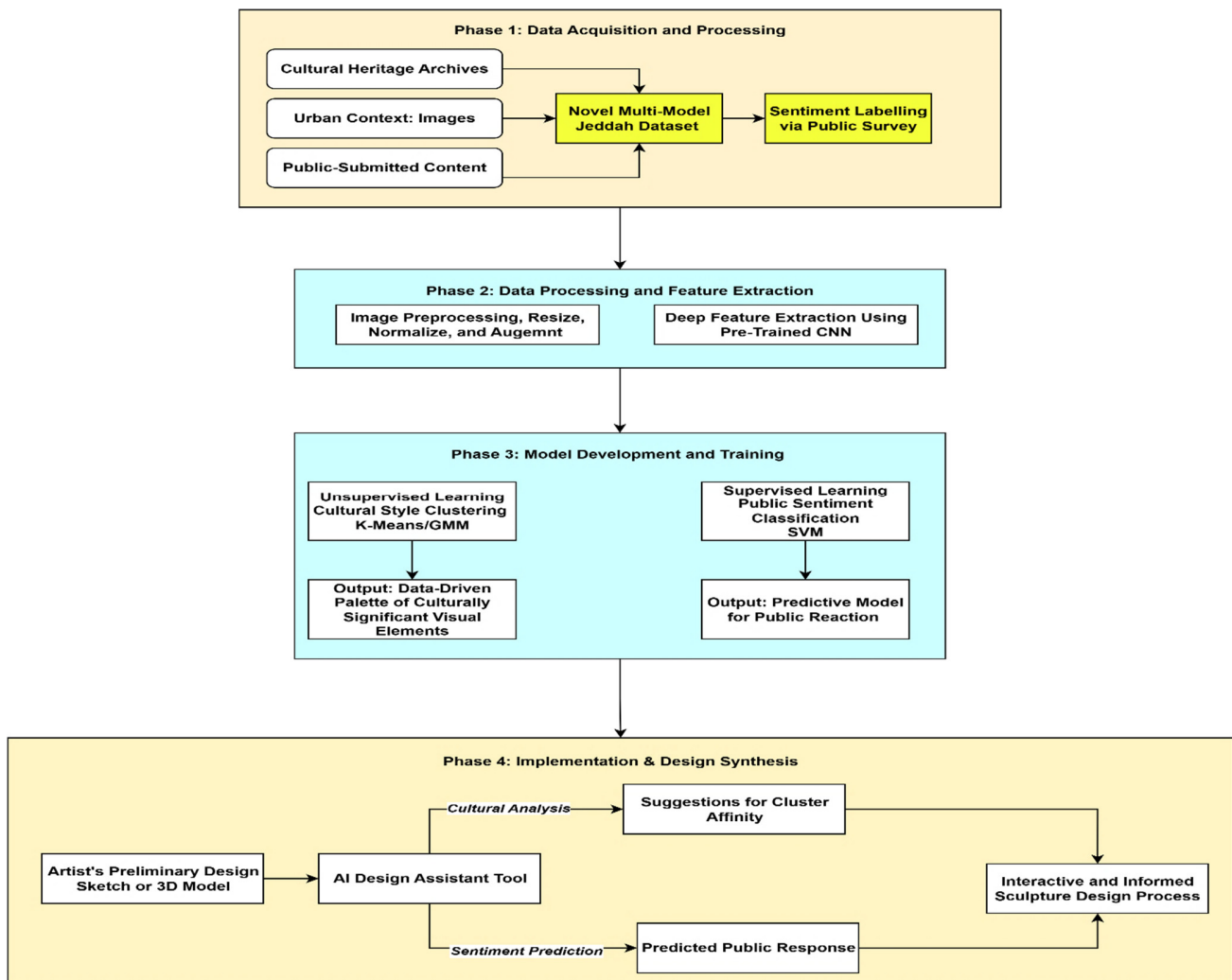


Fig. 1. Hybrid deep learning framework for AI-assisted design of culturally sustainable sculptures in Jeddah.

- Phase 3: Model development and training - This stage employs a hybrid learning approach to analyze the extracted features from two key perspectives. First, unsupervised learning algorithms (K-Means) were employed for cultural style clustering. This algorithm automatically detects patterns and groups the data into distinct clusters based on visual similarity, uncovering data-driven patterns of culturally important visual elements without prior labels. At the same time, supervised learning was used for public sentiment classification. Using the sentiment labels from Phase 1, a Support Vector Machine (SVM) model was trained to understand the relationship between visual features and public reception, resulting in a predictive model that can forecast the likely public response to new artistic elements.
- Phase 4: Implementation and design synthesis: The final phase translates the AI's analytical output into practical tools for artists and designers. It provides cultural analysis suggestions based on style clusters, guiding the artist toward design elements with strong cultural affinity. AI

Design Assistant Tool integrates these insights, creating an interactive environment where an artist can input a preliminary design sketch or 3D model. The tool then provides a sentiment prediction forecast of the public response based on the trained model. This facilitates an informed and interactive sculpture design process, allowing the artist to iteratively refine their work with an evidence-based understanding of its cultural resonance and potential public reception before the final implementation.

IV. IMPLEMENTATION OF THE DEVELOPED MODEL

The model was implemented by conducting a case study of designing a new public sculpture for the Jeddah Corniche (Waterfront) that resonates with Jeddah's cultural identity and receives positive public reception.

A. Phase 1: Data Acquisition and Processing

In phase I of the study, a multi-modal dataset, the "Jeddah Cultural-Artistic Corpus", was created with the following details:

- Image Data ($n = 5,000$): Sourced from museum archives (e.g., traditional Najdi and Hijazi art, Islamic geometry), photos of existing Jeddah sculptures (e.g., the famous Jeddah Fountain, works by artists like Sameh Al Tawil), and images of Jeddah's historic Al-Balad district and modern skyline.
- Public Sentiment Data: An online survey is distributed where 1,200 participants rate a subset of 500 images on a 5-point scale (1: Strongly Dislike, 5: Strongly Like) based on cultural significance and aesthetic appeal.

This data collection resulted in a labeled dataset where each image is associated with visual content, metadata (e.g., traditional, modern, abstract, figurative), and an average Public Sentiment Score (PSS).

B. Phase 2: Data Preprocessing and Feature Extraction

All 5,000 images were resized to 224×224 pixels and normalized. Data augmentation (rotation, flipping) was applied to increase the dataset size and robustness. A pre-trained ResNet-50 CNN model (trained on ImageNet) was used to extract deep features from the second-to-last layer, producing a 2048-dimensional feature vector for each image. The ResNet-50 architecture was selected for feature extraction due to its proven performance and efficiency.

The raw pixel data were transformed into a numerical matrix of 5,000 rows (images) \times 2,048 columns (features). These features represent high-level visual concepts, such as textures, shapes, and patterns, relevant to Jeddah's art.

C. Phase 3: Model Development and Training

This phase involves two parallel modeling tasks: unsupervised learning and supervised learning.

1) Unsupervised Learning: Cultural Style Clustering:

During this task, K-Means was selected for cultural style clustering due to its efficiency and interpretability on high-dimensional image feature data, allowing for clear, distinct group identification. The optimal number of clusters ($k = 4$) was determined using the elbow method, as illustrated in Table II.

The unsupervised learning process produced four clusters as follows:

- Cluster 0: Traditional Islamic: Characterized by geometric patterns (arabesque), calligraphy, and traditional motifs.
- Cluster 1: Modern Abstract: Characterized by bold, non-representational shapes and contemporary materials (steel, glass).
- Cluster 2: Coastal/Organic: Characterized by flowing lines, wave-like forms, and blue/earth tone color palettes.
- Cluster 3: Figurative/Historical: Characterized by representations of people, boats (dhows), and historical scenes. It is noteworthy that the figurative art identified in this cluster predominantly features historical and nautical themes, navigating cultural considerations by focusing on

narrative and heritage elements rather than religious or individual portraiture.

TABLE II. CULTURAL STYLE CLUSTERS SUMMARY

| Cluster | Label | Key characteristics | Example source imagery |
|---------|-----------------------|--------------------------------------|-------------------------------------|
| 0 | Traditional Islamic | Arabesque, calligraphy, symmetry | Al-Balad architecture, Quranic art |
| 1 | Modern Abstract | Bold shapes, steel/glass, minimalism | Modern Jeddah sculptures |
| 2 | Coastal/Organic | Flowing lines, waves, blue tones | Red Sea coral, dunes, dhows |
| 3 | Figurative/Historical | Human forms, dhows, narratives | Historical photos, older sculptures |

2) Supervised Learning: Public Sentiment Prediction

For sentiment prediction, an SVM model was chosen for its effectiveness in high-dimensional spaces and strong performance on binary classification tasks. A grid search with 5-fold cross-validation was employed to tune the hyperparameters. The dataset was split by 80/20 for training and testing. The model achieved strong performance, with an accuracy of 85%. The model achieved a precision of 87%, a recall of 83%, and an F1-score of 85%. The outcomes of supervised learning are:

- The model achieved an 85% accuracy on the test set in predicting whether the public will like a new design.
- Feature importance analysis reveals that images with features associated with Cluster 0 (Traditional Islamic) and Cluster 2 (Coastal/Organic) have the strongest positive correlation with high PSSs.
- The trained model was able to predict sentiment scores for new, unseen images.

D. Phase 4: Implementation and Design Synthesis

In this phase, the AI Design Assistant Tool was created, after which a sculptor starts designing a concept for the Corniche by inputting an initial sketch of a modern, abstract spiral form into the tool.

E. Prototype AI Tool Output

1) Cultural Analysis

The initial design most visually resembles Cluster 1 (Modern Abstract). For greater cultural resonance, it was proposed to incorporate elements from high-sentiment clusters, along with geometric patterns from Cluster 0 (e.g., perforated screen with an Islamic pattern). The sculptor was also proposed to soften the rigid form into more flowing, wave-like curves inspired by Cluster 2.

2) Sentiment Prediction

The sculptor followed suggestions and refined the sketch to have a flowing, wave-like silhouette, adding a subtle pattern inspired by traditional Mashrabiya screens, leading to a 62% probability of positive public reception.

F. Simulated AI Tool Output (2nd Iteration)

In the second iteration, the design demonstrated a strong affinity with Cluster 2 and a moderate affinity with Cluster 0, which is a highly proposed combination. The new design had an 89% probability of positive public reception.

The sculptor finally achieved the final design: "The Red Sea Mirage", a flowing, wave-like sculpture crafted from polished steel, with subtle laser-cut patterns that cast intricate shadows reminiscent of traditional Islamic art, as shown in Figure 2. The AI model provided evidence-based guidance, ensuring that the final artwork is innovative, culturally grounded, and predicted to be well-received by the Jeddah community.



Fig. 2. The final sculpture, 'The Red Sea Mirage,' incorporates the AI's key suggestions.

V. RESULTS AND DISCUSSION

Applying the proposed framework to the Jeddah Corniche case study produced significant results. These results showcase the model's practical viability and create opportunities for discussion on the links between AI, cultural preservation, and urban planning. The outcomes of this study are:

A. Data-Driven Identification of Culturally Significant Styles

The unsupervised learning model (K-Means clustering) successfully designed the curated "Jeddah Cultural-Artistic Corpus" into four distinct, semantically meaningful clusters without prior human labeling. This objective, data-driven analysis revealed the core visual languages present in Jeddah's artistic and architectural landscape.

B. Measurement of Public Sentiment and Its Correlations

The supervised learning model (SVM classifier) achieved a high accuracy rate of 85% in predicting public reception based on visual features. The feature importance analysis uncovered a powerful insight: designs incorporating visual elements from Cluster 0 (Traditional Islamic) and Cluster 2 (Coastal/Organic)

showed the strongest positive correlation with high PSSs, as displayed in Table III.

TABLE III. CORRELATION BETWEEN CULTURAL CLUSTERS AND PSS

| Cultural cluster | Label | Key characteristics | Correlation with high PSS |
|------------------|------------------------|--------------------------------------|---------------------------|
| 0 | Traditional Islamic | Arabesque, calligraphy, symmetry | Strong Positive |
| 1 | Modern Abstract | Bold shapes, steel/glass, minimalism | Neutral/Weak Negative |
| 2 | Coastal/Organic | Flowing lines, waves, blue tones | Strong Positive |
| 3 | Figurative/ Historical | Human forms, dhows, narratives | Moderate Positive |

The strong positive correlation between Cluster 0 (Traditional Islamic) and Cluster 2 (Coastal/Organic), characterized by high public sentiment, is culturally significant. Traditional Islamic patterns are deeply rooted in the region's heritage and spiritual identity, evoking a sense of authenticity and continuity. Similarly, the Coastal/Organic forms directly reference Jeddah's historical and economic relationship with the Red Sea, creating an immediate emotional connection to the local landscape and collective memory. Conversely, the neutral or weak negative correlation with Cluster 1 (Modern Abstract) suggests that designs perceived as lacking an apparent cultural or environmental reference may be viewed as generic or disconnected from local identity, despite their artistic merit. This explains the successful outcome of the case study: the final design synthesized the familiarity of tradition and place (Clusters 0 and 2) with the novelty of a modern form, achieving innovation within a culturally recognizable framework.

C. Successful AI-Assisted Iterative Design Process

The case study demonstrated the practical utility of the AI Design Assistant Tool. The initial modern abstract design received a modest prediction of 62% probability of positive public reception. By integrating the AI's evidence-based suggestions, specifically incorporating flowing, organic lines from Cluster 2 and subtle traditional patterns from Cluster 0, the sculptor iteratively refined the design. The final design, "The Red Sea Mirage," experienced a dramatic increase in its predicted positive reception, jumping to 89%.

This study reveals a functional link between cutting-edge technology, such as AI, and deeply ingrained cultural traditions. The findings confirm that the proposed AI model is not merely a theoretical concept but a practical tool that can effectively analyze cultural aesthetics, predict public sentiment, and guide the creation of culturally sustainable public art.

D. Limitations and Future Work

Although this study highlights the potential of the proposed framework, it is imperative to acknowledge its current limitations. The primary constraint involves the inherent bias present in the initial "Jeddah Cultural-Artistic Corpus," which, despite meticulous selection, may not comprehensively encompass the full spectrum of the city's diverse cultural

expressions. Furthermore, the model's generalizability is deliberately confined to the specific context of Jeddah; its application to other cities, such as Riyadh, or different cultural regions, necessitates the development of a new, localized dataset and subsequent retraining of the models. Finally, the AI Design Assistant Tool remains at the prototype stage, and its scalability for extensive use by urban planners and artists encounters practical challenges concerning software integration, computational demands, and user experience design.

These limitations, however, lay the groundwork for valuable future research. To decrease dataset bias and enhance the generalizability of the findings, an essential subsequent step involves expanding the corpus to incorporate 3D models along with a more diverse array of demographic and sub-cultural data from various regions within the Kingdom. The scalability of the framework can be enhanced by transforming it into a standardized software plugin compatible with widely used 3D design applications and by conducting comprehensive testing of its adaptability in other Saudi cities, such as Diriyah or Al-Ula, to optimize its applicability for broader cultural contexts.

VI. CONCLUSION

This study demonstrates that the proposed hybrid deep learning framework serves as a practical, evidence-based tool for integrating Artificial Intelligence (AI) with cultural preservation, effectively addressing a key gap in sustainable urban art design. By utilizing unsupervised learning to identify core aesthetic clusters unique to Jeddah's identity, and supervised learning to gauge public sentiment, the framework provided actionable guidance that increased a sculpture's predicted public approval from 62% to 89% in a real-world case study. This provides a scalable model to support Saudi Vision 2030's cultural goals. Future research will concentrate on incorporating advanced generative AI models, such as GANs or Diffusion Models, to produce more detailed and varied design alternatives. A primary goal is to develop a method that leverages these models, for example, by using ControlNet with Stable Diffusion to conditionally generate designs based on detected cultural clusters, thereby effectively linking data-driven analysis with creative generation.

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DATA AVAILABILITY STATEMENT

The data used in this study are subject to licensing agreements that strictly prohibit redistribution.

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