



Digital-Twin-Oriented Surrogate Modelling of Architectural Identity and Thermal Performance in Benghazi A Semi-Physical, Evidence-Informed Framework for Multi-Objective Design-Space Exploration

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Received: 10/8/2026 Revised: 13/8/2026 Accepted: 05/9/2026 Publication: 05/10/2026

Abstract

This study develops a Digital-Twin-oriented computational framework for exploring relationships between selected architectural-envelope characteristics, thermal performance, and a limited evidence-informed proxy of architectural identity in Benghazi. The framework integrates documented historical geometric evidence with a semi-physical thermal formulation, tree-based machine-learning surrogates, permutation importance and SHAP analysis, and a 50,000-point Monte Carlo design-space exploration followed by Pareto analysis. HistGradientBoosting achieved an independent-test R^2 of 0.98940, RMSE of 0.29227 °C, and MAE of 0.23646 °C, while five-fold cross-validation produced a mean R^2 of 0.98815 ± 0.00116 . Wall thickness and external temperature were the dominant thermal predictors within the current formulation. The documented geometric evidence from the Sidi Khrebish/Berenice context showed substantial variability, with a weighted empirical mean ratio of 1.37453 (SD = 0.24723); the Golden Ratio ($\phi \approx 1.618$) was therefore retained as an independent comparative geometric reference rather than embedded in the base APII. The multi-objective exploration produced a computational Pareto set of 16 non-dominated solutions under standardized conditions of 35 °C outdoor temperature and 800 W/m² solar irradiance. A computational compromise was selected with wall thickness of 0.592982 m, WWR of 0.104893, arch ratio of 1.415982, predicted indoor temperature of 26.546933 °C, APII of 98.604171/100, and independent Golden Ratio proximity of 87.512504/100. These results remain exploratory and model-dependent; they represent surrogate fidelity to the defined semi-physical formulation rather than field validation of real buildings.

Keywords: Digital Twin; semi-physical surrogate model; machine learning; HistGradientBoosting; SHAP; permutation importance; AIPI; architectural identity; Benghazi; Monte Carlo; Pareto; Golden Ratio.

الملخص العربي

تهدف هذه الدراسة إلى تطوير إطار حسابي موجّه نحو التوائم الرقمي لاستكشاف العلاقة بين بعض الخصائص الهندسية للغلاف المعماري والأداء الحراري ومؤشر وكيل محدود للهوية المعمارية في بنغازي يدمج الإطار الأدلة الهندسية التاريخية المتاحة مع نموذج حراري شبه فيزيائي، ونماذج تعلم آلة شجرية ، وتحليل تفسيري باستخدام Permutation Importance و SHAP، ثم يستكشف فضاء تصميم افتراضي يضم 50,000 حالة باستخدام Monte Carlo و تحليل Pareto، حقق HistGradientBoosting على مجموعة الاختبار المستقلة $R^2 = 0.98940$ و $RMSE = 0.29227\text{ }^{\circ}\text{C}$ و $MAE = 0.23646\text{ }^{\circ}\text{C}$ ، بينما بلغ متوسط R^2 في التحقق المتقاطع الخماسي 0.98815 ± 0.00116 . أظهر تحليل الأهمية أن سماكة الجدار ودرجة الحرارة الخارجية هما المتغيران الأكثر تأثيراً في الاستجابة الحرارية ضمن الصياغة الحالية ، كما أظهرت الأدلة الهندسية الموثقة في سياق Sidi Khrebish/Berenice تبايناً واضحاً في النسب، بمتوسط تجريبي موزون قدره 1.37453 ، ولذلك تم فصل ϕ Golden Ratio (1.618) باعتبارها مرجعاً هندسياً مقارناً مستقلاً عن AIPI. وأسفر التحليل متعدد الأهداف عن مجموعة حلول Pareto ، ثم تم اختيار حل توافقي حسابي بلغت فيه سماكة الجدار 0.592982 m ، و $WWR = 0.104893$ ، ونسبة القوس 1.415982 ، ودرجة الحرارة الداخلية المتوقعة $26.546933\text{ }^{\circ}\text{C}$ ، و $AIPI = 98.604171/100$ ، والتقارب المستقل مع النسبة الذهبية $87.512504/100$. وتبقى هذه النتائج استكشافية ومقيدة ببنية النموذج والبيانات شبه الفيزيائية ، ولا تمثل تحققاً ميدانياً لمبانٍ حقيقية.

الكلمات المفتاحية :التوائم الرقمي؛ النمذجة شبه الفيزيائية؛ تعلم الآلة؛ HistGradientBoosting؛ SHAP؛ Permutation Importance؛ AIPI؛ الهوية المعمارية؛ بنغازي؛ Monte Carlo؛ Pareto؛ Golden Ratio.

1. Introduction

Benghazi provides a relevant context for studying architectural identity because its built environment contains multiple historical and cultural layers, while recent scholarship describes architectural identity as a combination of physical and non-physical characteristics whose expression varies by place and time (Safour & Elmazek, 2024). More recent heritage research also emphasizes the role of historic buildings and urban context in Benghazi's architectural memory and identity (Safour et al., 2025).

The present study translates a limited subset of architectural characteristics into quantitative variables so that they can be explored jointly with thermal-response variables. The objective is not to reduce architectural identity to a single number, but to construct an auditable computational proxy from the evidence that can currently be quantified. Machine learning is used as a surrogate-modelling layer rather than as a replacement for architectural or heritage interpretation.

The framework is deliberately described as Digital-Twin-oriented rather than as a fully operational Digital Twin. Current Digital Twin literature emphasizes connections between physical and digital representations, data integration, applications, and operational challenges (Mousavi et al., 2024;

AlBalkhy et al., 2024). The present study does not yet include a live building, sensor stream, or continuously updated operational data source.

2. Research Problem

The central problem is how to explore selected architectural-identity characteristics and thermal performance within a common quantitative design space while maintaining a clear distinction between computational results and empirically validated building performance. The current thermal data are synthetic/semi-physical, and the identity component is evidence-informed but limited by the availability of quantitative historical documentation.

The research question is therefore: How can an initial Digital-Twin-oriented computational framework combine documented architectural evidence, a semi-physical thermal model, machine-learning surrogates, and multi-objective exploration without presenting model-derived results as validated claims about real buildings?

3. Objectives and Hypotheses

The objectives are to: (1) develop a semi-physical indoor-temperature model; (2) compare tree-based machine-learning surrogates using an independent hold-out set; (3) assess stability through five-fold cross-validation; (4) interpret predictor contributions using permutation importance and SHAP; (5) construct a limited evidence-informed AIPI from documented geometric evidence; (6) explore 50,000 virtual configurations using Monte Carlo sampling; and (7) identify a Pareto frontier and a computational compromise for subsequent physical validation.

H1 states that a tree-based model can accurately approximate the defined semi-physical thermal relationship. H2 states that increasing wall thickness reduces predicted indoor temperature within the current formulation and comparable boundary conditions. H3 states that the framework can identify a design region representing a trade-off between thermal performance and the operational identity proxy. H4 treats the Golden Ratio as a comparative geometric reference rather than as a historically established rule.

4. Previous Studies and Theoretical Position

Digital Twin reviews emphasize the importance of linking physical and digital layers, data integration, applications, and validation challenges (Shahzad et al., 2022; Mousavi et al., 2024; AlBalkhy et al., 2024). Accordingly, the present contribution is positioned as an intermediate computational framework that can later be connected to measured buildings and independent simulation.

For architectural identity, Benghazi-specific studies establish that architectural and urban character reflects place, time, and cultural context rather than a single universal form (Safour & Elmazek, 2024). Archaeological evidence from Sidi Khrebish provides directly documented and estimated room proportions and courtyard-related spatial evidence (Michaelides, 1998). Pye (1974) further documents material and wall-plaster evidence from House H. These sources are used as evidence layers, not as proof of a universal Benghazi architectural standard.

5. Historical Evidence and AIPI

The historical evidence review distinguishes between measured, estimated, and qualitative documentation. Fourteen room-proportion observations from Sidi Khrebish/Berenice were retained in the computational geometric reference distribution. Measured observations receive weight 1.0 and estimated/reconstructed observations receive weight 0.5. The resulting weighted empirical mean is 1.37453 and the weighted empirical standard deviation is 0.24723.

The resulting Evidence-Informed Architectural Identity Proxy Index (AIPI) currently represents geometric compatibility with this documented empirical distribution. It is not a direct measurement of cultural identity. Other potentially relevant characteristics—including WWR as a heritage target, limestone preference, courtyard presence, and façade rhythm—are retained as contextual evidence unless sufficient quantitative evidence exists to assign defensible numerical scores. The Golden Ratio is deliberately excluded from the base AIPI and evaluated independently.

6. Methodology

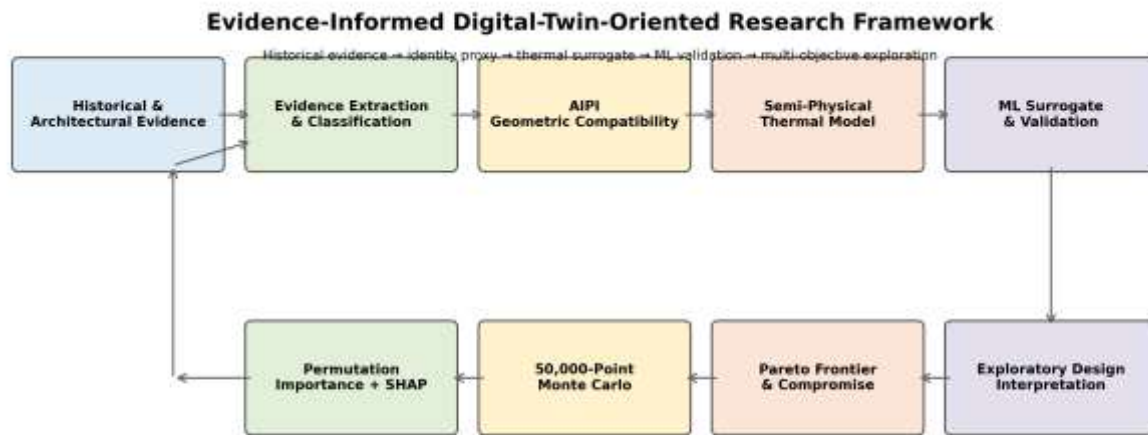


Figure 1. Research methodology: historical and architectural evidence → AIPI → semi-physical thermal model → machine-learning surrogate and validation → Monte Carlo exploration → Pareto analysis and exploratory design interpretation.

The workflow consists of two linked streams. The historical-evidence stream collects plans, archaeological measurements, photographs, maps, and published descriptions, then classifies the evidence and extracts only variables with sufficient quantitative support. The computational stream generates semi-physical thermal cases, trains and evaluates machine-learning surrogates, applies explainability methods, and explores the virtual design space using Monte Carlo and Pareto analysis.

The thermal design space includes wall thickness of 0.20–0.60 m, WWR of 0.10–0.45, arch ratio of 1.00–2.00, outdoor temperature of 28–42 °C, and solar irradiance of 500–950 W/m². The thermal formulation uses wall and glazing conductance, solar heat gain, a simplified damping factor, and a stochastic residual. It does not explicitly model orientation, solar position, shading geometry, ventilation, infiltration, humidity, wind, occupancy, internal gains, or detailed thermal mass.

The dataset is divided into 80% training and 20% independent hold-out test data. Five-fold cross-validation is performed within the training subset. The compared models are GradientBoosting, HistGradientBoosting, and ExtraTrees. Model evaluation uses R², RMSE, and MAE. Permutation importance and SHAP are interpreted as model-explanation measures rather than causal effects (Pedregosa et al., 2011; Lundberg & Lee, 2017).

For multi-objective exploration, 50,000 virtual configurations are evaluated under standardized summer conditions of 35 °C outdoor temperature and 800 W/m² solar irradiance. The Pareto problem minimizes predicted indoor temperature and maximizes AIPI. A normalized distance to the ideal point is then used to select a computational compromise; this selection is not a universal optimum or construction specification.

7. Results

7.1 Performance on the independent test

Table 1. Performance of the tree-based surrogate models on the independent test set.

Model	R²	RMSE (°C)	MAE (°C)
HistGradientBoosting	0.98940	0.29227	0.23646
GradientBoosting	0.98924	0.29437	0.23596
ExtraTrees	0.98826	0.30751	0.24423

HistGradientBoosting achieved the highest R^2 on independent testing, with a 5-fold CV $R^2 = 0.98815 \pm 0.00116$, CV RMSE = 0.29066 °C, and CV MAE = 0.23022 °C.

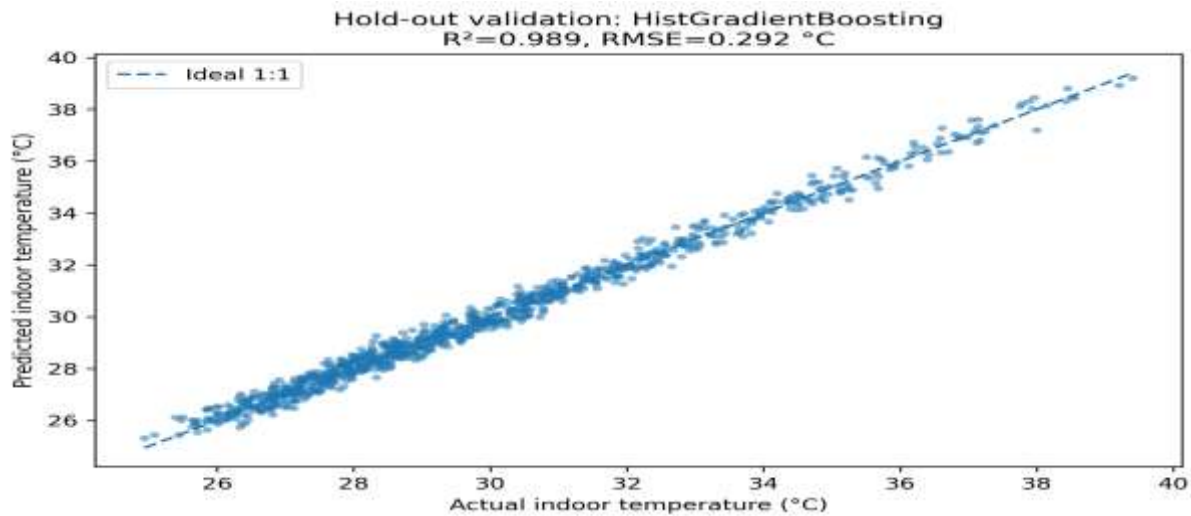


Figure 2. Hold-out validation: actual versus predicted indoor temperature.

7.2 Comparison of tree-based surrogate models

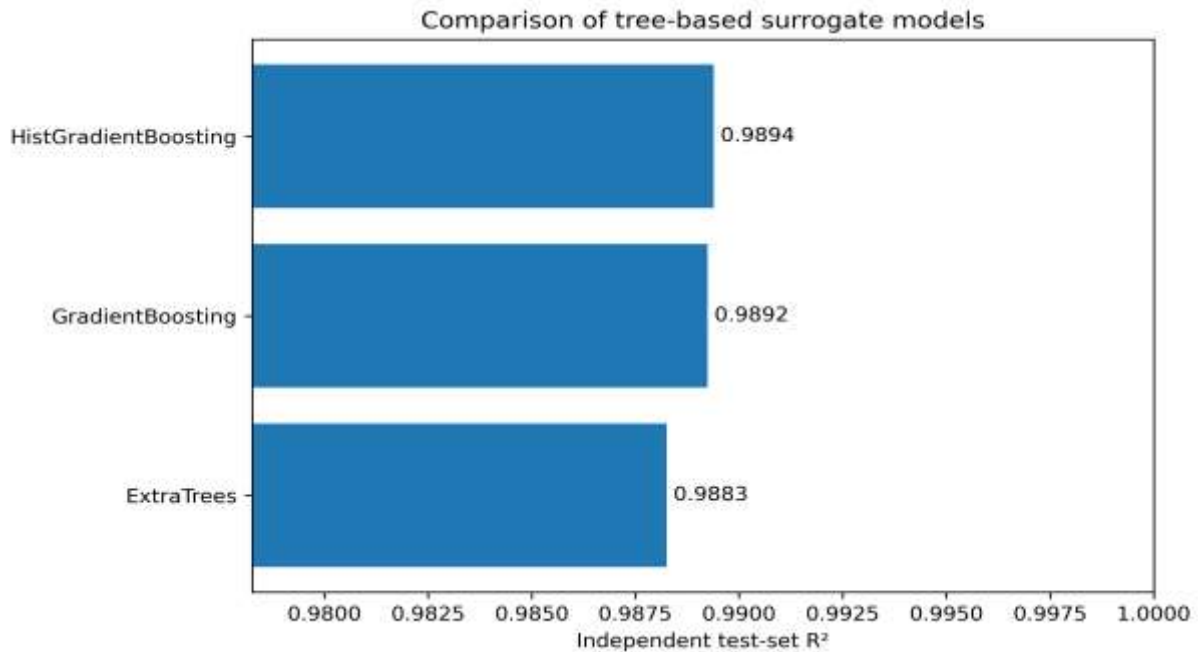


Figure 3. Comparison of tree-based surrogate models on the independent test set.

7.3 Permutation Importance

Table 2. Permutation importance of thermal surrogate inputs on the independent test set.

Feature	Mean Importance	Std
Wall_Thickness	1.12805	0.04357
External_Temp	0.86841	0.03633
Window_to_Wall_Ratio	0.02367	0.00151
Solar_Irradiance	0.01017	0.00078
Arch_Ratio	-0.00004	0.00007

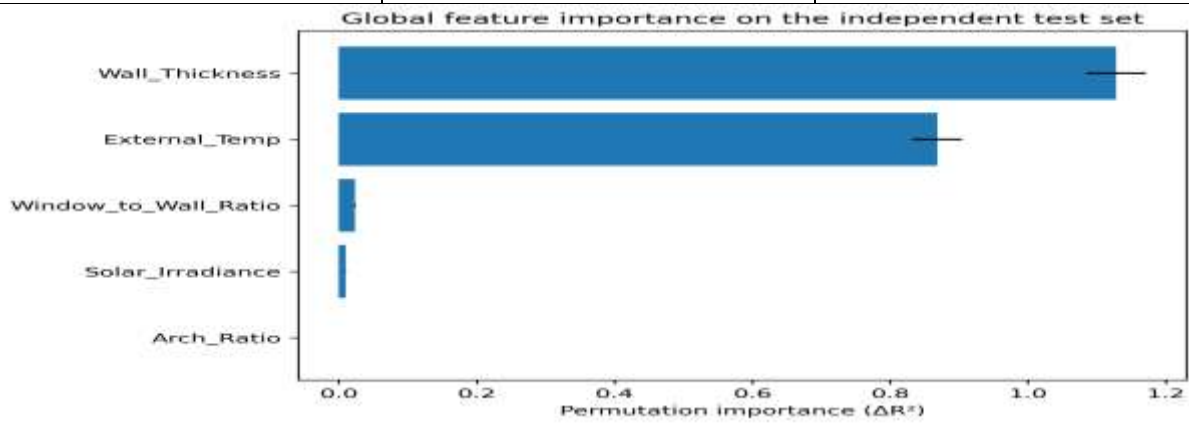


Figure 4. Permutation importance of thermal surrogate inputs on the independent test set.

7.4 SHAP Analysis

Table 3. Global SHAP importance of the thermal surrogate inputs.

Feature	Mean SHAP
Wall_Thickness	1.65704
External_Temp	1.41880
Window_to_Wall_Ratio	0.22867
Solar_Irradiance	0.15146
Arch_Ratio	0.01597

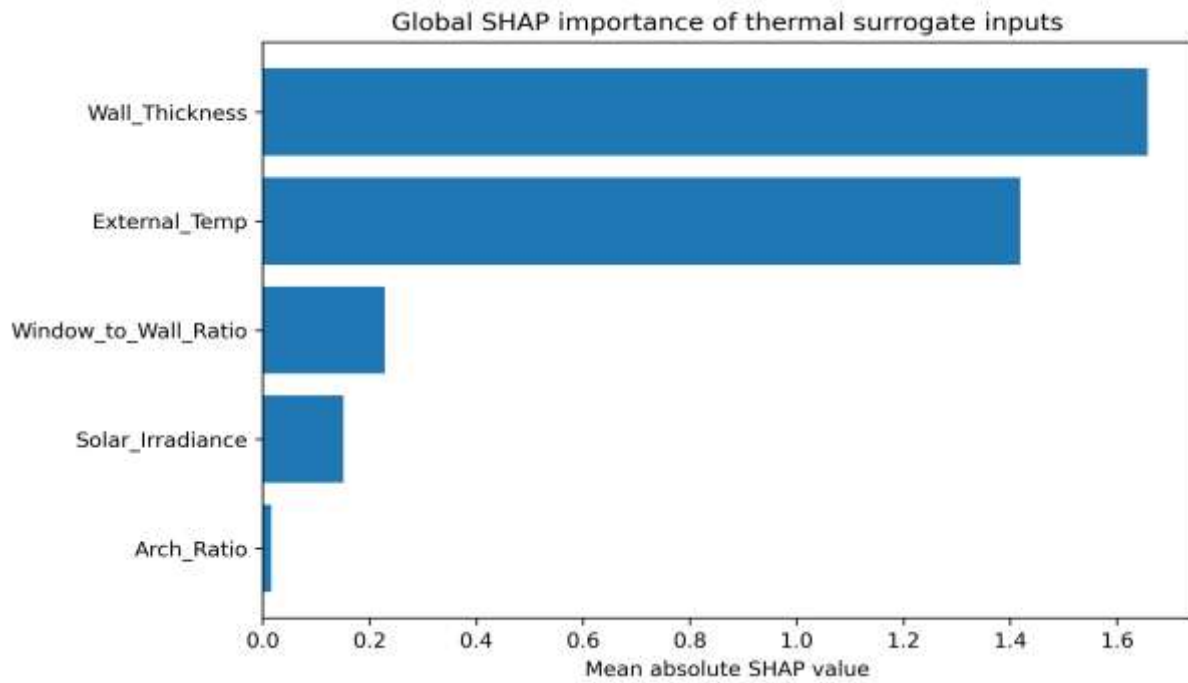


Figure 5. Global SHAP importance of thermal surrogate inputs..

7.5 Historical geometric evidence

Table 4. Documented geometric evidence from Sidi Khrebish/Berenice used to construct the empirical reference distribution.

Observed ratio	Evidence	Context	Weight
1.033	Measured	House H Room 4	1.0
1.365	Measured	House H Room 5	1.0
1.596	Estimated	House H Room 7	0.5
1.821	Measured	House H Room 8	1.0
1.218	Estimated	House R3 Room 5	0.5
1.426	Estimated	House S1 Room 1	0.5
1.667	Estimated	House S2 Room 1	0.5
1.545	Estimated	House P1 Room 1	0.5
1.367	Estimated	House P1 Room 2	0.5
1.125	Estimated	House P1 Room 3	0.5

1.333	Estimated	House P1 Room 11	0.5
1.125	Estimated	House P3 Room 7	0.5
1.444	Estimated	House P3 Room 10	0.5
1.083	Estimated	House P3 Room 11	0.5

Weighted empirical mean = 1.37453; weighted empirical SD = 0.24723.

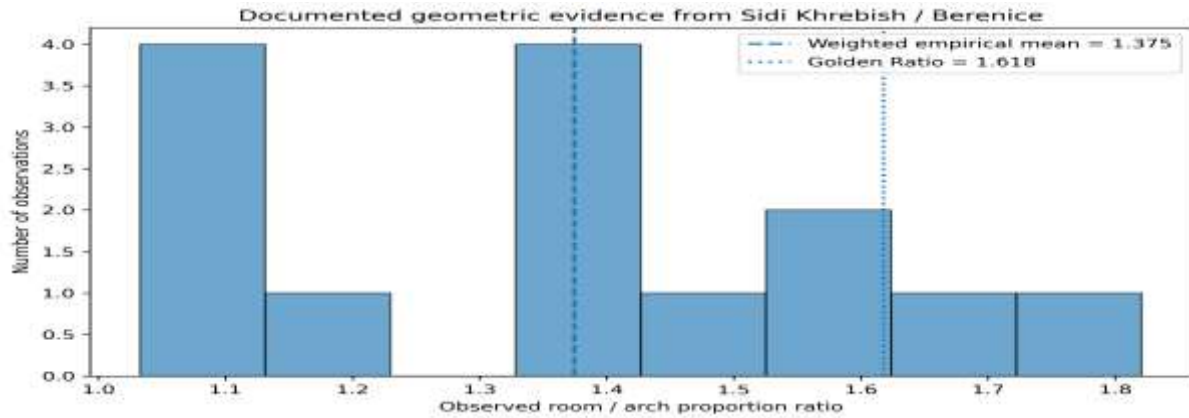


Figure 6. Documented geometric evidence from Sidi Khrebish/Berenice.

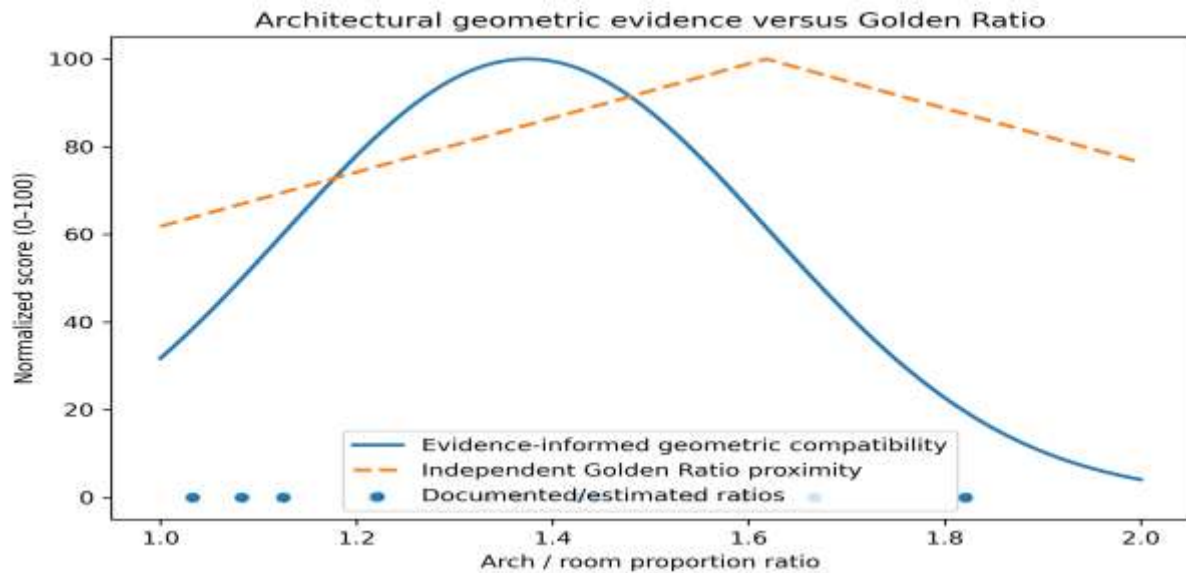


Figure 7. Evidence-informed geometric compatibility versus independent Golden Ratio proximity.

7.6 Monte Carlo and Pareto

Table 5. Computational compromise configuration identified from the Monte Carlo Pareto exploration.

M = 50,000; WWR range = 0.10–0.45; outdoor temperature = 35 °C; solar irradiance = 800 W/m². The latest reported run identified a computational Pareto set and the following compromise configuration.

Parameter	Compromise value
Wall thickness	0.592982 m
WWR	0.104893
Arch ratio	1.415982
Predicted indoor temperature	26.546933 °C
AIPI	98.604171 / 100
Golden Ratio proximity	87.512504 / 100
Distance to ideal	0.020221

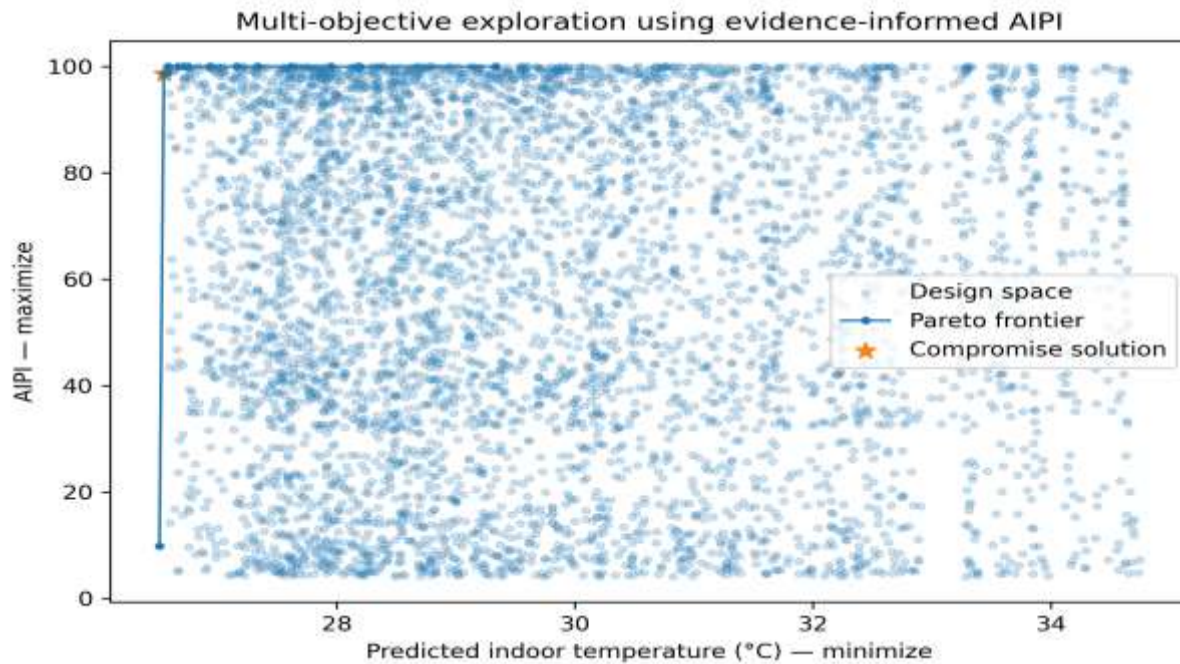


Figure 8. Multi-objective exploration using evidence-informed AIPI and the Pareto frontier.

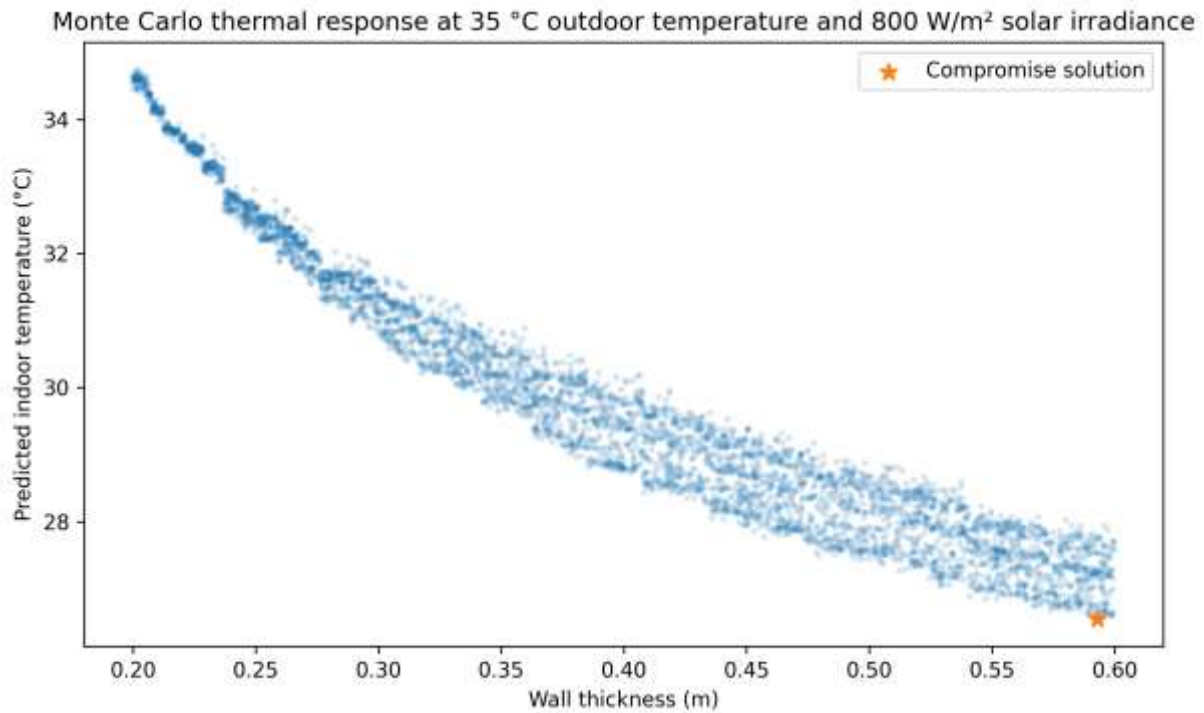


Figure 9. Monte Carlo thermal response as a function of wall thickness.

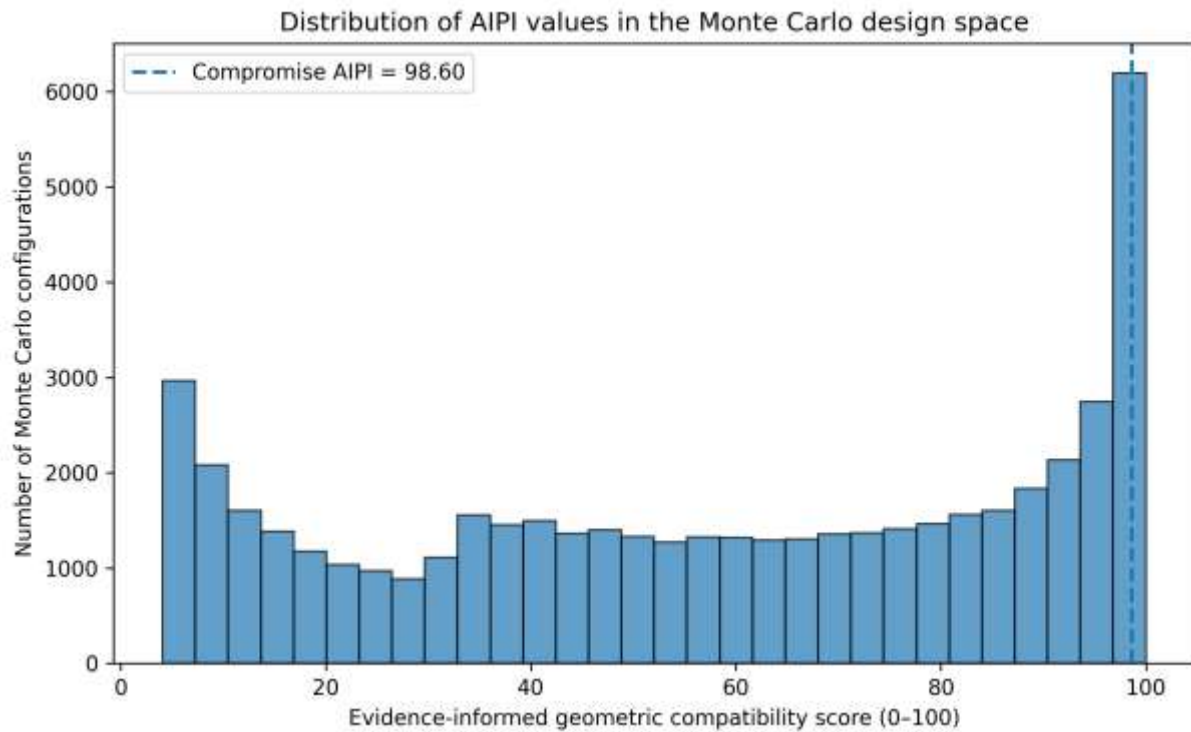


Figure 10. Distribution of AIPI values in the Monte Carlo design space.

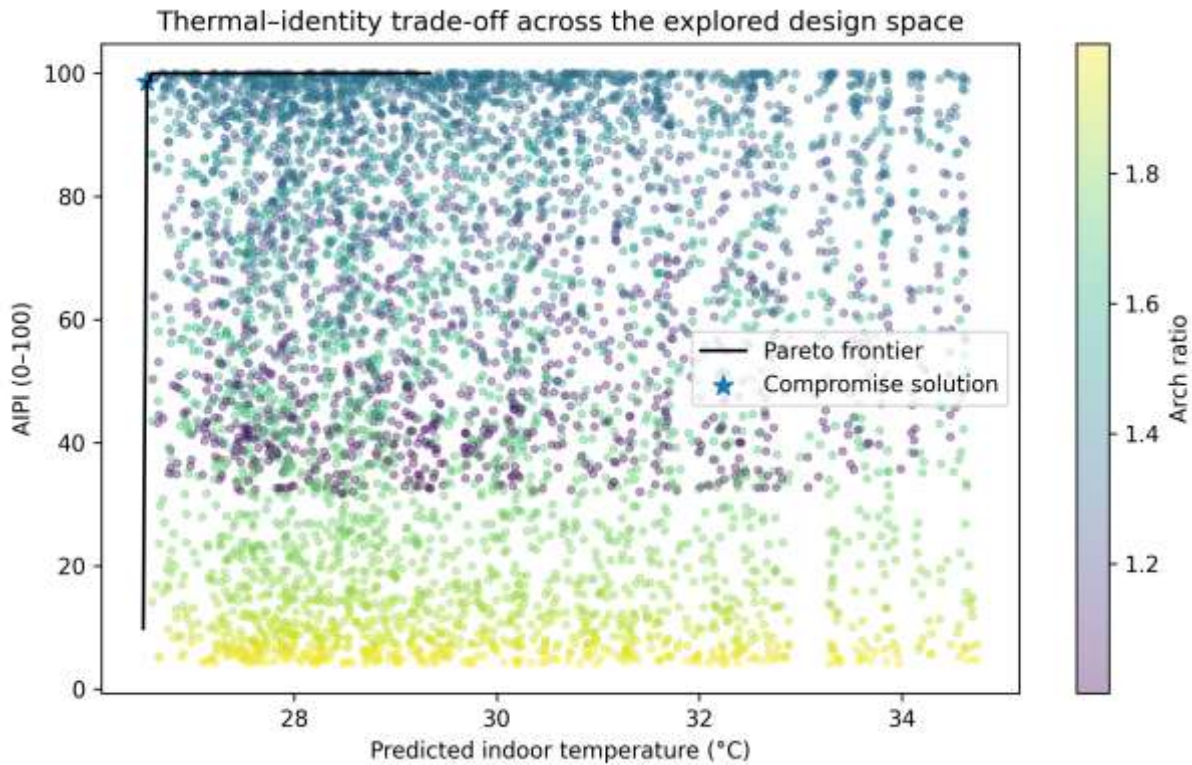


Figure 11. Thermal–identity trade-off across the explored design space.

HistGradientBoosting was selected as the surrogate model. On the independent test set it achieved $R^2 = 0.98940$, $RMSE = 0.29227$ °C, and $MAE = 0.23646$ °C. Five-fold cross-validation produced $R^2 = 0.98815 \pm 0.00116$, $RMSE = 0.29066$ °C, and $MAE = 0.23022$ °C. The high performance indicates strong fidelity to the defined semi-physical target function, not independent physical validation.

Permutation importance ranked wall thickness first (1.12805), followed by outdoor temperature (0.86841), WWR (0.02367), solar irradiance (0.01017), and arch ratio (−0.00004). SHAP showed the same broad pattern: wall thickness 1.65704, outdoor temperature 1.41880, WWR 0.22867, solar irradiance 0.15146, and arch ratio 0.01597. The low thermal contribution of arch ratio is expected because arch ratio does not directly enter the current thermal equation; its principal role is in the architectural-identity pathway.

The latest Monte Carlo run produced 16 non-dominated Pareto solutions. The selected compromise was: wall thickness = 0.592982 m; WWR = 0.104893; arch ratio = 1.415982; predicted indoor temperature = 26.546933 °C; AIPI = 98.604171/100; Golden Ratio proximity = 87.512504/100; distance to ideal = 0.020221.

8. Discussion

The results indicate that the machine-learning surrogate can reproduce the semi-physical thermal formulation with high numerical accuracy. However, because the target variable is generated by the model itself, the reported R^2 and error metrics should be interpreted as surrogate fidelity. They do not demonstrate that a real Benghazi building would achieve the same thermal response.

The historical evidence provides a more defensible basis for the geometric identity component than the former rule-based score because it derives the reference distribution from documented archaeological dimensions. Nevertheless, the evidence is concentrated in Sidi Khrebish/Berenice and combines measured and estimated observations. The AIPI should therefore be interpreted as a limited geometric compatibility indicator rather than as a complete measure of Benghazi architectural identity.

The compromise arch ratio of 1.415982 does not establish the Golden Ratio as a historical rule. The independent Golden Ratio proximity score of 87.512504/100 is simply a comparative geometric measure. The distinction is important because embedding ϕ directly into the identity function would otherwise make apparent convergence toward ϕ partly circular.

The compromise solution also lies close to the upper wall-thickness boundary and lower WWR boundary of the sampled space. This boundary-seeking behavior reflects the current mathematical formulation and imposed design limits. It should not be interpreted as a universal prescription for wall thickness or window area.

9. Hypothesis Assessment

H1 is supported within the defined semi-physical surrogate space. H2 is supported conditionally within the current thermal formulation. H3 is supported exploratorily through the identification of a Pareto set and a computational compromise. H4 is supported only as a comparative analysis: the current results do not establish the Golden Ratio as a historical or universal characteristic of Benghazi architecture.

10. Limitations and Recommendations

The principal limitations are the synthetic/semi-physical thermal dataset, the simplified heat-balance formulation, the absence of field measurements, the restricted quantitative historical evidence, and the limited scope of AIPI. Future work should collect measured architectural and environmental data; add orientation, shading, glazing, ventilation, infiltration, occupancy, humidity, wind, and thermal-mass variables; validate the surrogate against independent dynamic simulation and field observations; and expand the historical evidence base across different periods and building types.

Additional identity components should be introduced only when sufficient evidence exists to quantify them. Material comparisons should use independently documented thermal and environmental

properties rather than imposed preferences. The Golden Ratio should remain an independent comparative criterion unless future evidence demonstrates a historically justified role.

11. Conclusion

The revised framework provides a reproducible computational route for linking documented architectural evidence, semi-physical thermal modelling, machine-learning surrogates, explainability, and multi-objective design exploration in Benghazi. The latest run demonstrates high surrogate fidelity, a documented empirical geometric reference, and a Pareto-based design-space exploration with 16 non-dominated solutions. The principal scientific contribution is methodological: it separates historical evidence from modelling assumptions, separates AIPI from the Golden Ratio, and distinguishes computational exploration from physical validation. The next stage is therefore empirical calibration and independent validation rather than further enlargement of the synthetic dataset.

12. Historical Evidence, Images, and Maps

This section documents the historical, archaeological, photographic, plan, and map evidence used to contextualize the framework and to support the evidence-informed geometric component of AIPI. Evidence is explicitly distinguished as measured, estimated, qualitatively documented, or contextual. Not all historical evidence enters the numerical model.

12.1 Historical Evidence Source Register



Figure / historical photograph source note. Historical photograph of the former Benghazi Municipality Hall, used here as contextual architectural evidence rather than as a quantitative measurement source. Source: Australian War Memorial, Accession No. 006528, photograph by James Francis (Frank) Hurley, 1 March 1941; the Australian War Memorial identifies the item as public domain.

Table 6. Historical evidence layers and their role in the current computational framework.

Case / Layer	Evidence role	Quantitative status	Use in current model
Sidi Khrebish / Berenice	Ancient archaeological geometric evidence	Measured + Estimated ratios	Core geometric reference
Souq al-Hout / Old City	Ottoman/traditional urban context	Documented qualitatively	Context / stratification
Benghazi Municipality	Ottoman + later/Italian interventions	Documented qualitatively	Context / façade evidence
Al-Manar Palace	Italian colonial layer	Documented qualitatively	Historical stratification
Benghazi Cathedral	Italian colonial architecture	Plan/documentation available	Comparative layer
Maydan al-Shajara	Italian + later urban transformation	Historical imagery	Urban context
Maydan al-Baladiya	Multi-period urban core	Historical imagery / documentation	Urban context

The reviewed cases are treated as a stratified evidence set rather than as a homogeneous architectural sample. Sidi Khrebish/Berenice provides the quantitative geometric reference currently used by AIPI; the other cases broaden the historical and urban context but are not converted into numerical identity scores without sufficient quantitative evidence.

12.2 Historical evidence use and primary-source register

Table 7. Historical evidence use and primary-source register.

Case / layer	Evidence used in study	Evidence status	Primary source / citation
Sidi Khrebish / Berenice	Room plans and documented/estimated room proportions; courtyard organization; archaeological context	Measured + Estimated	Michaelides (1998), Sidi Khrebish/Berenice, Vol. IV.1; JSTOR open-access record.
Souq al-Hout / Old City	Historic municipal building and Ottoman/Italian stratification; contextual heritage evidence	Documented qualitatively	ASOR CHI Incident Report LHI 17-0013 (2017); Safour et al. (2025).
Benghazi Municipality Hall	Historic façade and urban-context evidence; photograph used for contextual illustration	Documented qualitatively	Australian War Memorial, Accession 006528 (1941); Safour et al. (2025).
Al-Manar Palace	Italian-period architectural layer and urban-context evidence	Documented qualitatively	Coccoli et al. (2024); World Monuments Fund; historical image sources listed below.
Benghazi Cathedral	Architectural-plan/context evidence for Italian-period layer	Plan/documentation available	Coccoli et al. (2024); Wikimedia Commons plan by Czechoriche (2020), CC BY-SA 4.0.
Maydan al-Shajara	Historical urban-square imagery and Italian-period context	Historical imagery	Wikimedia Commons historical Piazza Cagni image; contextual architectural source consulted during evidence review.
Maydan al-Baladiya	Historic/current square imagery and old-city context	Historical imagery / documentation	Wikimedia Commons; Safour et al. (2024, 2025).

12.3 Image, Plan, Map, and Archival-Source Traceability Register

Table 8. Image, plan, map, and archival-source traceability register.

Item used / consulted	Source	Date / creator	Use and rights note
Historical photograph of Benghazi Municipality Hall	Australian War Memorial, Collection C28251, Accession 006528 Source: https://www.awm.gov.au/collection/C28251	1 Mar 1941; James Francis (Frank) Hurley	Public domain according to AWM. Used as contextual evidence; no dimensions inferred from the photograph.
Benghazi Cathedral architectural plan	Wikimedia Commons, “Benghazi Cathedral Architectural Plan.jpg” Source: https://commons.wikimedia.org/wiki/File:Benghazi_Cathedral_Architectural_Plan.jpg	2020; Czechoriche	CC BY-SA 4.0. Attribution required; if adapted, the adapted work must comply with the license.
Maydan al-Shajara / Piazza Cagni historical photograph	Wikimedia Commons, “Maydan Shajara Piazza Cagni During Italian Rule.jpg” Source: https://commons.wikimedia.org/wiki/File:Maydan_Shajara_Piazza_Cagni_During_Italian_Rule.jpg	Italian colonial period, 1911–1941; author not stated	Public-domain status stated on the file page. Used only for historical/contextual comparison.
Maydan al-Baladiya photograph	Wikimedia Commons, “Maydan al Baladiya.jpg” Source: https://commons.wikimedia.org/wiki/File:Maydan_al_Baladiya.jpg	2009; AJL	Own-work photograph released under the licenses stated on the file page. Used as contemporary contextual imagery, not as a scaled measurement.
Ottoman Benghazi	Wikimedia Commons, “Mawlid Celebrations in Ottoman Benghazi.jpg” Source:	1896; author	Public Domain Mark stated on

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Municipality Square photograph	https://commons.wikimedia.org/wiki/File:Mawlid_Celebrations_in_Ottoman_Benghazi.jpg	unknown ; Benghazi Museum National Archive	the file page. Used as historical contextual evidence.
Al-Manar Palace / Piazza 28 Ottobre historical photograph	Wikimedia Commons, “Piazza 28 Ottobre, Bengasi.jpg” Source: https://commons.wikimedia.org/wiki/File:Piazza_28_Ottobre,_Bengasi.jpg	1930s; author unknown ; source noted as paolocason.it	Public-domain status stated on the file page. Used as historical contextual evidence.
Benghazi Town Hall colonial-period photograph	Wikimedia Commons, “Benghazi Town Hall During Colonial Rule.jpg” Source: https://commons.wikimedia.org/wiki/File:Benghazi_Town_Hall_During_Colonial_Rule.jpg	Before 1943; author not stated	Public-domain status stated on the file page. Use with the source and license information shown on the file page.
Sidi Khrebish plans and archaeological figures	Michaelides (1998), Figures section pp. 159–214 Source: https://www.jstor.org/stable/jj.14962420	1998; Demetrios Michaelides	CC BY-NC-ND 4.0 for the open-access book. Measurements were extracted from documented/scaled plans; figures are not altered or reproduced here without permission.
Benghazi historic-center contextual documentation	World Monuments Fund, “Benghazi Historic City Center” Source: https://www.wmf.org/monuments/benghazi-historic-city-center	WMF / ASOR and Libyan heritage partners	Institutional contextual source; used to document historic-center stratification and heritage context, not for quantitative

			architectural measurements.
Maydan al-Shajara current/context documentation	JE Architects, “Maydan al-Shajara” Source: https://je-architects.com/maydan-al-shajara	Web source	Contextual source consulted for the square and its historical urban setting; not used as a quantitative measurement source.

12.4 Map and Plan Use Protocol

Maps and plans are treated as evidence sources with an explicit distinction between scaled/measured material and contextual imagery. A plan is used quantitatively only when a documented scale or published dimensions support extraction. Photographs without a reliable scale are used for visual/contextual evidence only. Historical maps or plans reproduced from copyrighted or CC-licensed sources retain the original attribution and license conditions. The present AIPI computation uses the Sidi Khrebish geometric evidence; the other historical cases primarily establish stratification and contextual breadth and are not converted into numerical identity scores without sufficient quantitative evidence.

12.5 Figure and Source Traceability

Figures generated directly by the final computational pipeline are identified in their captions and correspond to the reported validation, model-comparison, feature-importance, historical-geometric, Monte Carlo, and Pareto analyses. Historical visual material is separately identified through the source register above. Quantitative measurements are extracted only from sources with documented dimensions or scale; unscaled photographs are used for contextual evidence only.

13. References

Historical visual and archival sources are additionally documented in Sections 12.1–12.4 so that image ownership, licensing, attribution, and evidentiary use remain traceable.

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