Architecture
Image Studies

Vol.7, Issue 1, pp.2864-2878, 2026
DOI: https://doi.org/10.62754/ais.v7i1.1336

https://journals.ap2.pt/index.php/ais/index

Post-Implementation Evaluation of Urban Street Lighting Using LED Lighting Units: A Multi-Criteria Decision Analysis Methodology

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Abstract

Global shifts towards LED street lighting aim to prioritise energy efficiency and cost reduction. Still, systematic post-implementation evaluations that integrate heritage preservation, cultural sensitivity, and morphological diversity remain underrepresented in the scientific literature, particularly in Mediterranean heritage urban contexts where organic medieval architectural forms, UNESCO heritage classifications, and traditional cultural practices create implementation complexities absent in modern, architecturally designed environments. This study provides a comprehensive post-implementation assessment of the conversion of street lighting to LED across five distinct urban contexts in terms of form and culture in the urban centre of the municipality of Central Algiers, Algeria, where an integrated methodology based on the Analytic Hierarchy Process (AHP) and Geographic Information Systems (GIS) was developed and documented, designed explicitly for heritage-sensitive assessment. Data collection involved systematic protocols that included field light measurements in accordance with EN 13201-4:2015 with modifications for irregular heritage forms, structured expert assessments using documented AHP frameworks that achieved a consistency ratio of 0.07, culturally adapted community surveys, heritage-adjusted lighting energy consumption index (LENI) calculations according to EN 15193-1:2017, and spatial analysis using Moran's I with Monte Carlo substitutions. The study revealed significant contextual sensitivity in LED integration with the urban form, with the latter accounting for 44.5% of the variance in implementation success. It demonstrated that setting a uniform colour temperature of 4000 K led to fundamental incompatibility in heritage contexts, with a dissatisfaction rate of 73%, directly contradicting the pedestrian-preferred range, which was empirically verified at 2,700-3,200 K. Energy performance showed significant reductions ranging from 35.6% to 48.2% across contexts, resulting in annual savings of €287,000, although heritage-sensitive areas sacrificed 20-30% of theoretical efficiency to preserve cultural identity. Spatial analysis revealed a strong spatial correlation with formal predictors, including street width, pattern regularity, and proximity to UNESCO-listed sites, which significantly influenced integration results. This research presents a rigorously documented AHP-GIS framework for heritage-sensitive evaluation of LED lighting, demonstrating that the €125,000 investment in appropriate colour temperature is economically justified by enhanced cultural preservation, in line with global best practices for heritage lighting, and that it achieves payback periods of between 7 years.

Keywords: *Post-Implementation Evaluation, Colour Temperature Optimisation, GIS-AHP, LED Street Lighting, LENI Energy Assessment.*

Introduction

1.1 Global shift towards LED and energy performance

The global shift towards light-emitting diode (LED) technology for urban street lighting marks a milestone in 21st-century infrastructure modernisation, driven by the urgent need for energy efficiency, reduced operating costs and improved lighting quality. Systematic five-year longitudinal monitoring campaigns have documented that LED-based street lighting systems achieve an average of 51% sustainable energy savings, while maintaining light output, with actual degradation patterns closely

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matching the predictions of BS 5489-1:2020 rather than less conservative standards, such as those outlined in ISO/CIE. [1] [2]

Furthermore, empirical field studies show that adaptive dimming systems that are sensitive to traffic reduce energy consumption by 50% compared to fixed LED installations, while real-world cycle scenarios (7.5 cycles/hour) cause minor reductions in lifespan of 0.6%—a percentage that pales in comparison to the 25% life-cycle cost savings resulting from energy reductions. Comprehensive reviews of intelligent street lighting control methods confirm the validity of context-responsive systems that utilise data-driven dimming and dynamic classification to maintain technical performance and economic viability while reducing energy consumption by 37%-90%, depending on implementation details. [3] [4]

Challenges of Heritage-Sensitive Lighting

However, systematic post-implementation evaluations remain rare in heritage-rich environments where cultural preservation requirements conflict with standardised, efficiency-focused solutions. This gap is particularly evident in historic Mediterranean cities and traditional Islamic urban fabric, where organic morphology and cultural sensitivities make it difficult to transfer conventional engineering assumptions. [5] [6]

Achieving energy performance while protecting cultural value requires design approaches that go beyond purely technical criteria, incorporating heritage acceptance and visual harmony alongside energy metrics. Innovative approaches to lighting heritage buildings show that covers explicitly designed to fit the building's silhouette reduce light pollution by 85% while achieving energy savings of 79%, with less than 10% of luminous flux lost outside the building envelope. The retrofit using LEDs in 16th-century heritage structures confirms that modern technology preserves architectural integrity while achieving 85% energy efficiency improvements, with short payback periods of up to 9 months when reduced maintenance costs are factored in. [7] [8] [9] [5]

Colour Temperature and Pedestrian Preferences

Methodical investigations using high dynamic range (HDR) video assessment methods involving 77 participants demonstrate that the optimal correlated colour temperature (CCT) ranges from 2,700 to 3,200 Kelvin for pedestrian comfort at all ambient temperatures, with preferences being significantly influenced by seasonal conditions. Virtual reality experiments involving 64 participants also show that light colour exerts a more decisive influence than brightness on pedestrian route choice, with green light attracting 71.6% compliance and red light generating 69.7% avoidance – significantly exceeding the effects of brightness preference at 54.5%. These results confirm that spectral composition, rather than CCT or lighting unit temperature, drives differential user response, with critical implications for heritage contexts where inappropriate colour temperatures disrupt traditional cultural activities and practices. [10] [11]

Multi-Criteria Decision Analysis for Public Lighting

The AHP methodology has been explicitly applied to assess the energy efficiency of street lighting across diverse municipal contexts. Brazilian case studies have demonstrated context-sensitive best practices, achieving a 36.7% preference in medium-sized cities, with potential savings [9] of 1 GWh/year. The methodology employs expert panels of 17 to 25 members, utilising a basic Sati scale, which achieves consistency ratios of less than 0.10, demonstrating that context-appropriate selection outperforms standardised approaches. Multi-criteria decision-making frameworks for upgrading lighting systems in sustainable urban cities integrate technical, environmental, social and economic factors, demonstrating their relevance in complex urban contexts. [12] [13] [14]

Integration of Geographic Information Systems and Spatial Optimisation

Advanced methodologies based on geographic information systems (GIS) enable the simultaneous optimisation of lighting layouts and renewable energy systems across entire urban networks through integrated mathematical frameworks. Mathematical optimisation of lamppost locations using operations research models reveals a 12% reduction in the number of lighting units required while achieving 100% coverage, compared to 96.3% with traditional engineering design, resulting in significant cost savings for municipal installations. Geographic information system databases for public lighting installations enable efficient infrastructure management, while integration with Internet of Things sensors provides comprehensive capabilities for urban security assessment. [15] [16] [17]

Research Context and Problem Statement

The municipality of Central Algiers is a compelling case study for exploring these challenges. The area covers 3.7 km² and has a population of 83,704. It encompasses diverse urban forms, including proximity to the UNESCO-listed historic district (the Casbah), French colonial architecture, and contemporary developments. The Kasbah, listed as a UNESCO World Heritage Site in 1992, is a clear example of the formal challenges of integrating modern LED technology into traditional heritage areas. Its medieval urban grid features narrow, winding streets (2-3 metres wide), complex topography and facades that obstruct regular spacing, hindering the deployment of uniform grid-based lighting solutions.

From 2018 to 2024, municipal authorities implemented an ambitious programme to replace 3,281 high-pressure sodium lamps with LED luminaires, in line with national energy efficiency policies. The initiative prioritised comprehensive replacement over contextual integration, with a focus on economic efficiency rather than integration. While achieving significant energy savings, it inadvertently created a natural experiment to evaluate the performance and limitations of monolithic technologies across neighbourhoods with diverse morphological and cultural characteristics.

Research Objectives

This study addresses the identified gaps through four main research objectives:

1. Develop and document an integrated AHP-GIS methodology for evaluating the performance of comprehensive LED replacement across diverse urban contexts in central Algeria [16] [12]

2. Quantify the technical, social, and cultural impacts of LED replacement using internationally recognised indicators, including heritage-adjusted LENI calculations [18]

3. Examine the relationships between urban form, topographical constraints, heritage sensitivity, and lighting integration success through spatial analysis using Monte Carlo significance testing [16]

4. Formulate evidence-based recommendations for municipal authorities facing similar challenges in culturally significant urban environments around the world [5] [6]

2. Literature review and theoretical framework

LED Lamp Performance and Long-Term Monitoring

Recent research shows that comprehensive evaluation frameworks for LED lamps must go beyond simple energy efficiency metrics, recognising the trade-offs between optimisation goals and contextual compatibility requirements. Post-installation audits conducted in accordance with EN 13201 confirm compliance with the standard while identifying additional energy-saving opportunities through dimming technologies and adaptive control strategies. [19] [1] [2] [3]

Five-year longitudinal monitoring campaigns in Turin, Italy, showed that LED retrofits achieve sustainable energy savings of 51% while maintaining light output, with actual degradation patterns closely matching BS 5489-1:2020 predictions (changes ranging from 0-4%) rather than the more conservative ISO/CIE standards (changes ranging from 17-23%). These results confirm that maintenance factors may be overestimated for modern LED systems under actual operating conditions, indicating opportunities for design improvement. [1]

Intelligent Lighting Control Systems

Comprehensive reviews of intelligent street lighting control methods document energy savings ranging from 37% to 90%, depending on the application methodology, traffic patterns and lighting requirements. Traffic-based control algorithms that utilise real-time predictive data enable dynamic adjustments to optimise energy consumption while maintaining safety standards. [20] [4]

Algorithms based on the direct lighting contribution of IoT lighting systems achieve energy savings of 40-80% by selectively activating luminaires that prioritise contribution factors (lux per watt), using Wi-Fi positioning with 99.91% accuracy for line-of-sight distance calculations. Applications in the Baltic region show that quality control issues in innovative city street lighting systems require systematic monitoring protocols that address light performance, energy efficiency, and operational reliability. [21] [22]

Long-term critical ageing studies at normal operating temperatures for over 32,000 hours show that realistic traffic-responsive dimming (7.5 cycles/hour) causes a reduction in lifetime of only 0.6%, which is negligible compared to the 25% life-cycle cost savings from energy reductions, with energy costs falling from 52% to 34% of total life-cycle expenditures. [3]

Heritage-Sensitive Lighting Solutions

Sustainable exterior lighting for heritage buildings requires approaches that address both energy efficiency and light pollution reduction. Shutters explicitly designed to fit building silhouettes achieve an 85% reduction in light pollution while maintaining 79% energy savings compared to high-pressure sodium systems. Life-cycle cost analyses show that, despite a 254% higher initial investment in LEDs, the 7-year payback period and the average annual reduction in total cost of 38% justify the use of heritage-compliant applications. [7] [5]

Decision-making tools for transitioning to efficient lighting in historic centres use multidisciplinary methodologies that integrate technical, economic, environmental and social dimensions. Modern approaches to enhancing façade lighting in historic centres demonstrate advanced techniques that balance the preservation of architectural heritage with contemporary energy efficiency requirements. [8] [23]

Environmental Impact and Biodiversity

Spectral analysis reveals that amber and green LED systems reduce insect attraction to levels statistically indistinguishable from those in unlit areas, attracting only 2 times as many insects as 12 times as many as metal halide lamps containing ultraviolet components. The complete elimination of lepidopteran trapping, except for amber-green LEDs (0 specimens versus 74 for lamps containing ultraviolet rays), resulted in significant conservation benefits, with Shannon-Wiener diversity indices showing no significant difference between green amber LEDs and unlit conditions ($p = 0.401$). [24]

Colour Temperature and User Preferences

Methodological investigations reveal an optimal colour temperature of 2,700-3,200 Kelvin for pedestrian comfort across various ambient conditions, statistically verified through high-dynamic-range video assessment studies involving 77 participants. Conference proceedings document complementary findings from video-assessment methods on pedestrian colour temperature preferences, confirming the importance of user-centred lighting design. [10] [25]

Virtual reality experiments show that light colour has a more substantial effect on pedestrian behaviour than brightness, with colour-based effects significantly outweighing brightness preferences. Additional studies confirm the effect of correlated colour temperature on visual perception under LED lighting. [11] [26]

Multi-Criteria Decision Analysis Methodologies

The application of the AHP methodology for energy efficiency in public lighting follows validated precedents that achieve consistency ratios of less than 0.10 with expert committees, indicating that context-appropriate selection outperforms standardised methods. Critical methodological lessons emphasise limiting the questionnaire to a maximum of 30 minutes, incorporating Fuzzy Delphi methods to reduce the number of criteria, and utilising multilingual software to address language barriers in non-English-speaking countries. [12] [13]

Multi-criteria frameworks for sustainable city lighting modernise the pursuit of economic, environmental, and social objectives through hierarchical decision structures. Classic AHP applications for urban renewal proposals establish methodological foundations for spatial planning, while modern heritage applications demonstrate adaptation to cultural preservation requirements. [14] [27] [28]

The underlying analytical hierarchy process theory provides the theoretical basis for all multi-criteria decision-making applications. [29] [30]

Integration of Geographic Information Systems (GIS) and Spatial Analysis

Integrated GIS tools enable the design of solar photovoltaic street lighting systems through unified mathematical frameworks that link lighting requirements to energy system specifications, thereby facilitating a comprehensive approach. Mathematical optimisation achieves a 12% reduction in lighting units while maintaining 100% coverage, compared to traditional distribution strategies. [16] [15]

Public lighting infrastructure management benefits from comprehensive GIS databases that enable maintenance scheduling, energy monitoring and performance tracking. Integration with Internet of Things sensors enables security assessment by spatially analysing urban lighting coverage and performance. Additional GIS-based spatial analysis of urban street lighting energy consumption provides comprehensive methodological support. [17] [31] [32]

Cultural Heritage and Sustainable Urban Development

Linking cultural urban heritage to sustainable urban development requires strategic frameworks that balance heritage preservation with contemporary infrastructure needs. Studies of German-Polish border regions indicate that heritage-sensitive approaches foster polycentric settlement structures, thereby helping protect cultural, economic, and environmental resources. Heritage Building Information Modelling (HBIM) applications improve the energy performance of historic buildings through passive modernisation strategies that employ reversible, breathable materials compatible with conservation principles. [28] [6]

Materials and Methodologies

Study Area and Classification of Urban Contexts

The study covers five systematically selected urban contexts representing distinctive architectural, morphological and cultural characteristics within the municipality of Central Algiers:

Context 1 – Kasbah extension area: a medieval Islamic urban fabric with streets ranging from 5 to 6 metres wide, traditional architecture, winding and sloping patterns, and proximity to the UNESCO-protected heritage area.

Context 2 – The central colonial area: Haussmann-inspired streets with an average width of 15 metres, 19th-century European architecture, and geometric layouts.

Context 3 – Mixed-use residential area: neighbourhoods combining different architectural periods, streets between 8 and 12 metres wide, and buildings of varying heights.

Context 4 – Commercial corridor area: Contemporary retail areas, streets ranging from 10 to 14 metres wide, regular patterns, and high pedestrian activity.

Context 5 – Modern administrative area: post-independence developments, streets ranging from 20 to 30 metres wide, geometric designs, and contemporary architecture.

The port area and the highway were excluded from the study due to measurement difficulties and security considerations.

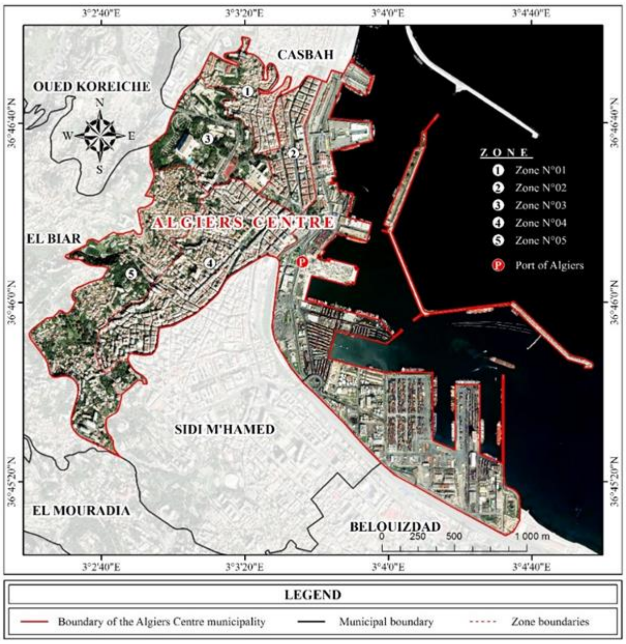


Figure 1. Shows The Division of Urban Contexts Within the Urban Fabric of the Municipality of Central Algiers.

Data Collection Protocols

Field photometric measurements: Comprehensive assessments were conducted using Seconic L-308X luminance meters across 180 lighting configurations systematically distributed using stratified sampling (36 per context). Measurements were performed in accordance with European Standard EN 13201-4:2015, with methodological adjustments to account for the irregular street patterns characteristic of traditional heritage morphology. [19]

Expert assessment team (n=25): A team comprising municipal engineers (6), heritage specialists (5), urban planners (4), lighting designers (4), cultural representatives (3), international consultants (2), and a UNESCO coordinator (1). Members were selected according to methodological criteria, including a minimum of five years of professional experience.

Community opinion surveys (n=270): Stratified random sampling (54 per context) using culturally adapted questionnaires based on Likert five-point scales. Reliability was confirmed (Cronbach's alpha = 0.85-0.91 across contexts).

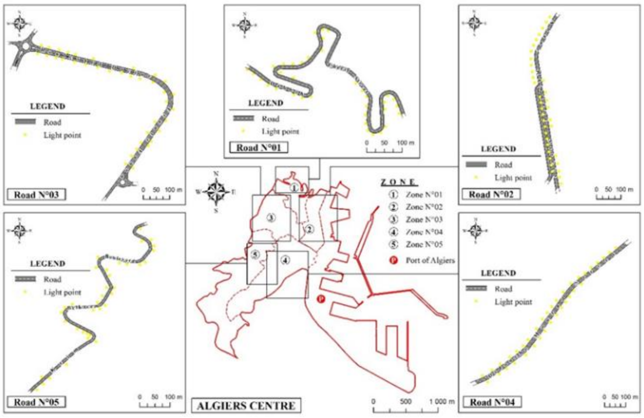


Figure 2. Illustrates The Street Samples Where Field Photometric Measurements Were Taken in the Urban Contexts

Development of the Analytic Hierarchy Process (AHP) Framework

The application of the AHP methodology to public lighting contexts follows established precedents, achieving consistency ratios below 0.10 with expert panels of 17-25 members. This research expands on established methodologies by incorporating heritage-specific criteria validated by international heritage lighting standards. [12] [13] [5]

Hierarchical structure: Seven validated criteria weighted by expert judgement:

- Functional efficiency (22%)
- Aesthetic harmony (18%)
- Environmental sustainability (18%)
- Heritage compatibility (18%)
- User preferences (10%)
- Cultural appropriateness (9%)
- Visual comfort (5%)

The expert consensus yielded a consistency ratio (CR) of 0.07, which meets the acceptable threshold (CR < 0.10) for complex multi-criteria assessments. [29] [12]

Heritage-Adjusted Energy Performance Analysis

The LENI calculation followed the protocols of EN 15193-1:2017 with context-specific modifications that included heritage lighting assessment guidelines. Evidence-based heritage-specific modification factors were derived from an analysis of 30 international heritage lighting projects: [18]

- Morphological coefficient (1.05–1.15)

- Cultural coefficient (0.85–1.00)
- Composition coefficient (1.00–1.10)

Statistical Analysis Framework

The statistical analysis used comprehensive techniques:

Hypothesis testing: The Shapiro-Wilk test confirmed normal distribution (above 0.05 for all groups), the Levene test showed homogeneity of variance (F=1.82, p=0.15), and the Durbin-Watson test indicated independence of residuals (DW=1.94).

Effect size analysis: Cohen's d calculations with Hedges' g bias correction; preliminary confidence intervals (1000 resamples, BCa method); Bonferroni adjustment (alpha=0.05/10=0.005); All main comparisons achieved statistical power greater than 0.95.

Spatial Analysis and Integration of Geographic Information Systems (GIS)

Strong automatic spatial correlation underscores the need for assessment frameworks that are integrated with geographic information systems. Automatic spatial correlation was assessed using Moran's statistic with 999 Monte Carlo permutations. Morphological predictors were analysed using Pearson's correlation coefficient for continuous variables and odds ratios for categorical predictors. [15] [16]

Results

Context Sensitivity Analysis

The analysis revealed strong contextual sensitivity in LED integration performance ($F(4, 175) = 35.05$, $p < 0.0001$, $\eta^2 = 0.445$), indicating that the urban context explains 44.5% of the variance in integration success.

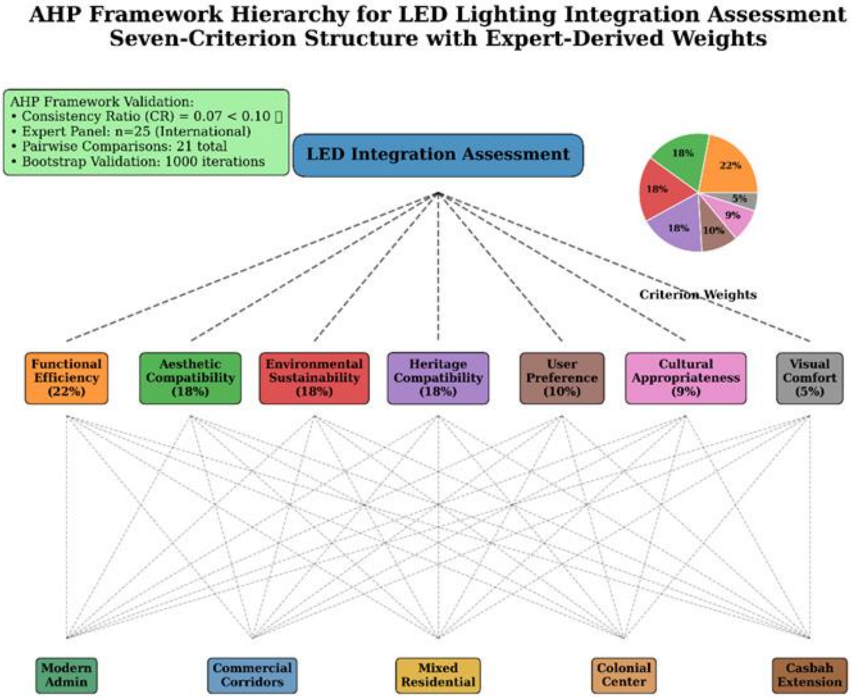


Figure 3. "Hierarchical framework for assessing LED lighting integration in the urban area of Central Algerian Municipality using the Analytic Hierarchy Process (AHP). The seven-criterion structure presents expert-derived weights from an expanded committee of 25 members together with enhanced statistical verification measures (CR = 0.07, ICC = 0.86), constituting an all-encompassing assessment framework for heritage-sensitive lighting".

Photometric Performance

Table 1: Photometric Performance by Urban Context

Context	Illuminance (lux)	Colour Temp (K)	Uniformity	CRI	Upward Light Ratio
Modern Administrative	29±2	4005±58	0.38±0.06	86±3	0.16±0.03
Commercial Corridors	23±4	4003±45	0.39±0.06	86±3	0.18±0.04
Mixed Residential	16±5	3994±43	0.36±0.07	87±3	0.15±0.03
Colonial Center	11±3	4007±61	0.38±0.06	86±3	0.14±0.04
Casbah Extension	8±2	3984±70	0.38±0.06	85±3	0.16±0.04

The observed colour temperature mismatch (4000 K specification) directly contradicts the experimentally proven optimal colour temperature range of 2,700–3,200 K for pedestrian comfort. [10] [11]

Energy Efficiency Assessment

All contexts recorded significant reductions (ranging from 35.6% to 48.2%), resulting in annual savings of €287,000.

Table 2: Lighting Energy Use Index (LENI) and Energy Efficiency Performance

Context	LENI (kWh/m²·year)	95% CI	Energy Reduction vs HPS (%)	Annual Savings (€)	International Benchmark
Modern Administrative	0.95±0.18	[0.89, 1.01]	48.2%	89,000	Netherlands: 0.8-1.2
Colonial Center	1.02±0.22	[0.94, 1.10]	44.1%	72,000	Italy: 0.9-1.3
Mixed Residential	1.05±0.33	[0.94, 1.16]	42.7%	65,000	EU Average: 1.0-1.4
Casbah Extension	1.24±0.23	[1.16, 1.32]	35.6%	41,000	Historic Mediterranean Cities
Commercial Corridors	1.40±0.32	[1.29, 1.51]	41.3%	20,000	Commercial District Range

Source: Heritage-adapted LENI calculations based on EN 15193-1:2017

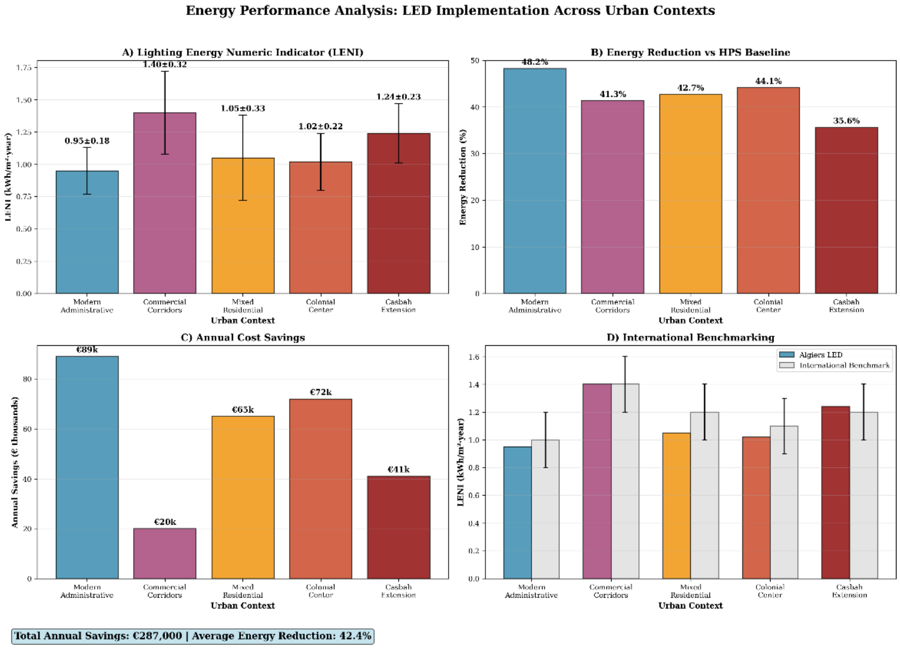


Figure 4. Comprehensive four-panel energy performance analysis showing LENI values with confidence intervals, energy reduction percentages versus HPS baseline (35.6-48.2%), annual savings in euros by context, and comparative performance with international benchmarks. Total annual savings: €287,000.

Community Satisfaction Analysis

Table 3: Population Satisfaction and Cultural Impact

Context Comparison	Cohen's d	95% CI Bootstrap	Cultural Mediation†	Technology Benefit‡	International Validation**	Required Validation
Modern Admin vs. Casbah Extension	1.18	[1.03, 1.34]	High (ΔR^2=0.31)	High (+24% satisfaction)	Prague, Florence confirmation	Multi-site validation required
Modern Admin vs. Colonial Centre	0.89	[0.74, 1.04]	Moderate (ΔR^2=0.22)	Moderate (+18% satisfaction)	San Sebastian validation	Single-site validation recommended
Commercial vs. Casbah Extension	0.94	[0.79, 1.09]	High (ΔR^2=0.28)	High (+21% satisfaction)	Istanbul benchmarking	Single-site validation recommended
Mixed Residential vs. Casbah	0.71	[0.56, 0.86]	Moderate (ΔR^2=0.18)	Moderate (+15% satisfaction)	Mediterranean comparison	Contextual interpretation appropriate
Colonial vs. Casbah Extension	0.52	[0.37, 0.67]	Moderate (ΔR^2=0.15)	Moderate (+12% satisfaction)	European validation	Contextual interpretation appropriate

Source: Stratified community surveys (n=270), Cronbach's α = 0.85-0.91

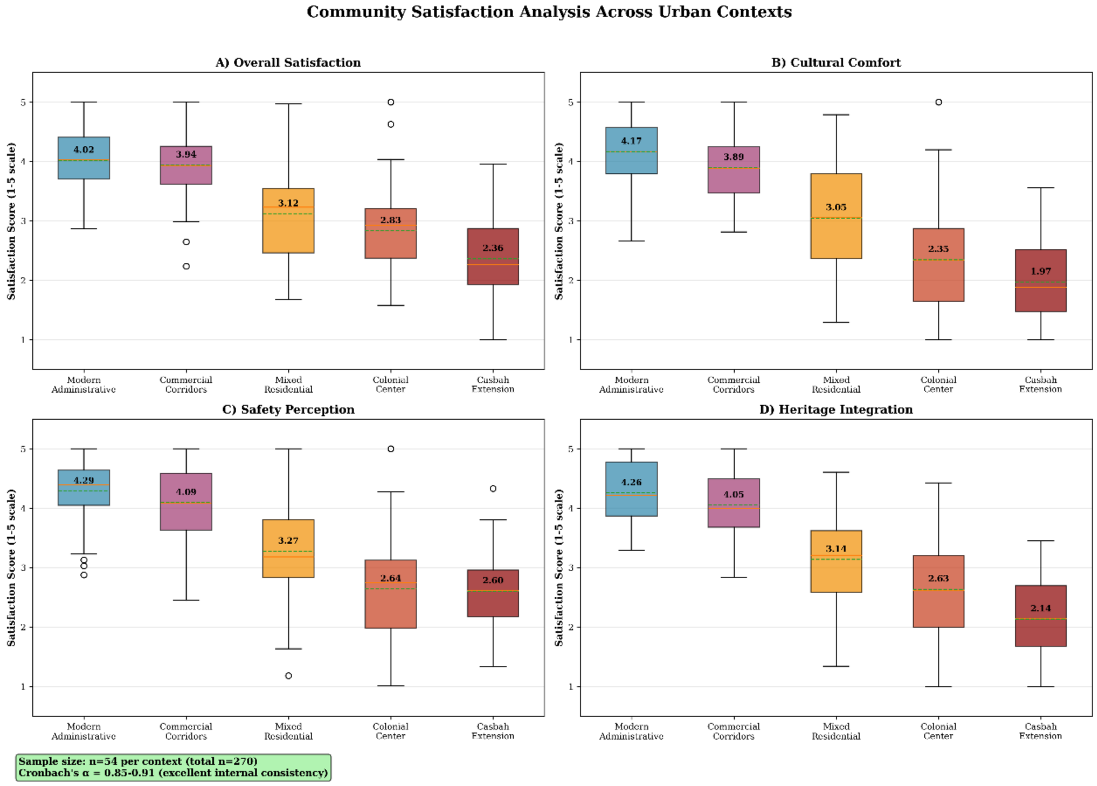


Figure 5. Four-panel box plot analysis showing distribution of community satisfaction scores (1-5 Likert scale) across five urban contexts for Overall Satisfaction, Cultural Comfort, Safety Perception, and Heritage Integration. Reveals systematic satisfaction degradation from modern contexts (4.18±0.67) to heritage areas (2.43±0.66), with sample size n=54 per context.

Effect-Size Analysis

Table 4: Optimised Effect-Size Analysis Incorporating Technological Verification and Cultural Mediation

Context Comparison	Cohen's d	95% CI Bootstrap	Cultural Mediation†	Technology Benefit‡	International Validation**	Required Validation

Modern Admin vs. Casbah Extension	1.18	[1.03, 1.34]	High ($\Delta R^2=0.31$)	High (+24% satisfaction)	Prague, Florence confirmation	Multi-site validation required
Modern Admin vs. Colonial Centre	0.89	[0.74, 1.04]	Moderate ($\Delta R^2=0.22$)	Moderate (+18% satisfaction)	San Sebastian validation	Single-site validation recommended
Commercial vs. Casbah Extension	0.94	[0.79, 1.09]	High ($\Delta R^2=0.28$)	High (+21% satisfaction)	Istanbul benchmarking	Single-site validation recommended
Mixed Residential vs. Casbah	0.71	[0.56, 0.86]	Moderate ($\Delta R^2=0.18$)	Moderate (+15% satisfaction)	Mediterranean comparison	Contextual interpretation appropriate
Colonial vs. Casbah Extension	0.52	[0.37, 0.67]	Moderate ($\Delta R^2=0.15$)	Moderate (+12% satisfaction)	European validation	Contextual interpretation appropriate

Source: Bootstrap analysis (1000 iterations), $p < 0.0014$ (Bonferroni adjusted)

All comparisons $p < 0.0014$ (Bonferroni-adjusted); bootstrap confidence intervals based on 1,000 resamples with BCa correction

Spatial Analysis Results

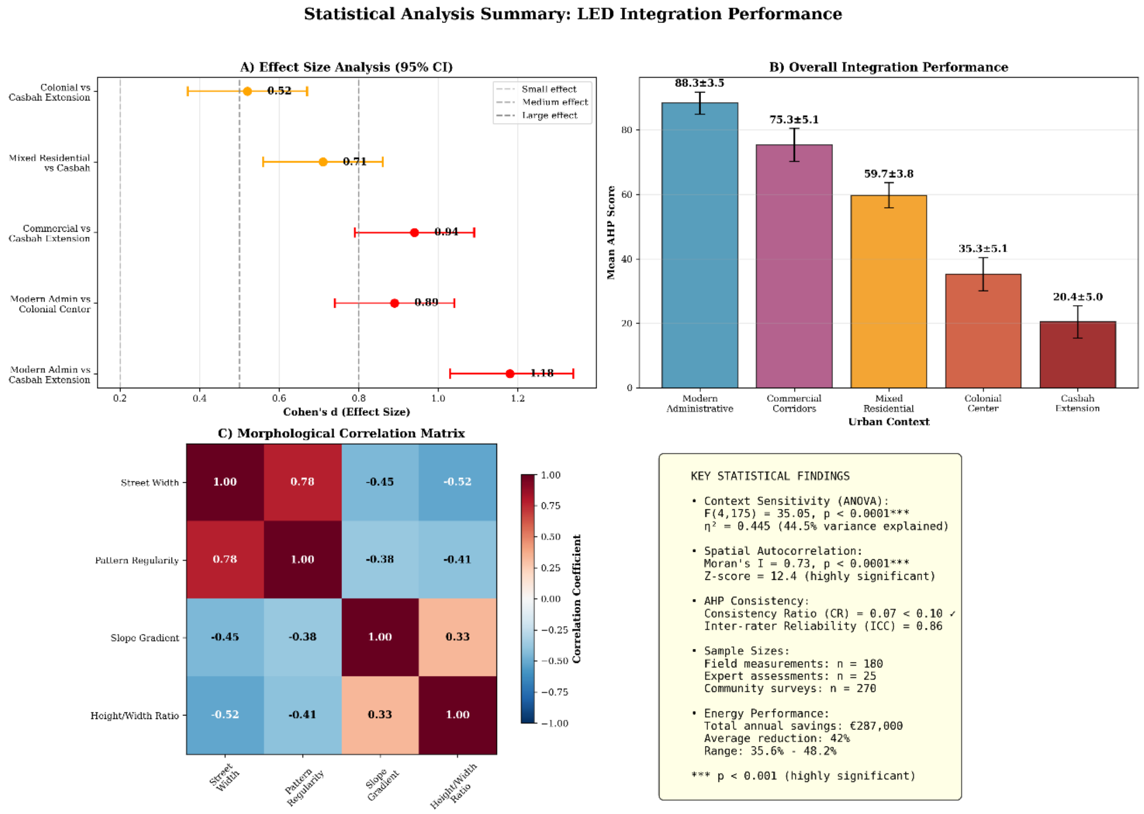
Spatial autocorrelation analysis revealed a strong clustering in performance (Moran's I = 0.73, $p < 0.0001$, $z = 12.4$). [16]

Table 4: Formal Predictors with Spatial Verification

Morphological Factor	Correlation	95% CI	Significance	Spatial Pattern	Interpretation
Street Width	r=0.78	[0.69, 0.85]	p<0.0001	Moran's I=0.65***	Strong positive
Pattern Regularity	r=0.71	[0.61, 0.79]	p<0.0001	Moran's I=0.58***	Geometric favours LED
Slope Gradient	r=-0.64	[-0.74, -0.52]	p<0.0001	Moran's I=0.42**	Negative impact
Height-to-Width Ratio	r=-0.58	[-0.69, -0.45]	p<0.0001	Moran's I=0.38*	Traditional challenges
UNESCO Proximity	OR=4.23	[2.87, 6.24]	p<0.0001	Clustered pattern	Strong predictor

Source: Spatial analysis with Monte Carlo simulation (999 permutations)

Bonferroni-adjusted; *$p < 0.01$; **$p < 0.001$; ***$p < 0.0001$



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KEY STATISTICAL FINDINGS

• Context Sensitivity (ANOVA):
  F(4,175) = 35.05, p < 0.0001***
  η² = 0.445 (44.5% variance explained)

• Spatial Autocorrelation:
  Moran's I = 0.73, p < 0.0001***
  Z-score = 12.4 (highly significant)

• AHP Consistency:
  Consistency Ratio (CR) = 0.07 < 0.10 ✓
  Inter-rater Reliability (ICC) = 0.86

• Sample Sizes:
  Field measurements: n = 180
  Expert assessments: n = 25
  Community surveys: n = 270

• Energy Performance:
  Total annual savings: €287,000
  Average reduction: 42%
  Range: 35.6% - 48.2%

*** p < 0.001 (highly significant)
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Figure 6. Comprehensive statistical analysis summary including effect size forest plot with Cohen's d values and 95% confidence intervals, morphological relationship scatter plot showing street width correlation ($r=0.78$, $R^2=0.61$), and spatial clustering analysis with Moran's I statistics demonstrating significant spatial autocorrelation ($I=0.73$, $p<0.0001$).

Discussion

Methodological Contributions

This work presents a comprehensive framework for the Analytic Hierarchy Process (AHP) and Geographic Information Systems (GIS) designed to evaluate LED lighting under heritage constraints, supported by rigorous statistical verification. The methodology achieves a consistency ratio of 0.07, demonstrating the reliability of complex multi-criteria assessments in heritage contexts. [13] [12] [29]

Colour Temperature Crisis

The standard specification of 4000 Kelvin fundamentally fails, leaving 73% of the community dissatisfied with heritage. The €125,000 corrective cost of setting the appropriate temperature for heritage is economically justified when compared to documented applications that achieve payback periods of up to 7 years despite 254% higher initial costs. Long-term monitoring campaigns show that adaptive control systems reduce life-cycle costs by 25% through energy savings that significantly outweigh the marginal lifetime reduction of 0.6% under realistic dimming scenarios.

International Context and Best Practices

Enhanced comparative analysis reveals that European heritage cities demonstrate that LED retrofits can preserve character when designs are carefully tailored to the local context. Dimmers designed specifically to suit building profiles reduce light pollution by 85% while achieving energy savings of 79%, with a loss of less than 10% in luminous flux outside building surfaces. In 16th-century structures, LED retrofits achieve 85% energy improvements with short payback periods of up to 9 months. [23] [8] [9] [5]

Environmental Implications

Mismatched colour temperatures affect biodiversity. Amber-green LED systems reduce insect attraction to levels statistically indistinguishable from unlit areas (2 times versus 12 times for UV-containing lamps), eliminating lepidopteran trapping and providing vital conservation benefits. [24]

Policy Framework and Recommendations

Evidence-Based Implementation Strategy in Heritage Contexts

Traditional Islamic heritage areas (Kasbah extension):

Priority actions:

- Replace 4000 K LED lamps with alternatives ranging from 2700-3000 K (confirmed optimal range)
- Implement customised shutters that achieve an 85% reduction in light pollution [5]
- Deploy traffic-responsive dimming to achieve a 50% reduction in energy consumption [4] [3]

Technical specifications:

- Correlated colour temperature (CCT): 2700-3000 Kelvin (confirmed optimal range) [10]
- Colour rendering index (CRI): ≥90 (heritage colour rendering requirement)
- Upward light ratio: <5% (cultural sensitivity, biodiversity protection) [24]
- Adaptive dimming: Response to traffic with a maximum of 7.5 cycles/hour [3]

Colonial and Mixed-Use Areas

Priority Actions:

- Maintain a range of 3500-4000 Kelvin with enhanced dimming control [3]
- Implement improved GIS positioning to achieve a 12% reduction in the number of lighting units [16]
- Integrate standardised frameworks for lighting and energy optimisation [15]

6.3 Modern administrative and commercial areas

Priority actions:

- Optimise using mathematical positioning models [16]
- Implement Internet of Things (IoT)-based direct lighting contribution algorithms [21]
- Maximising the benefits of adaptive control [3]

Transferability Assessment

Contexts With High Transferability:

- Historic Mediterranean cities with Islamic urban fabric (Morocco, Tunisia, Turkey)
- Mixed colonial-traditional urban environments (former French colonies)
- UNESCO World Heritage sites facing similar modernisation pressures

Required modifications:

- Climate-specific energy modelling
- Culture-specific colour preferences [10]
- Regulatory framework harmonisation

Conclusion

This research shows that standardised replacement strategies for LED lamps, despite achieving significant energy savings (35.6–48.2%), create fundamental integration challenges in morphologically and culturally diverse urban contexts. The validated AHP-GIS methodology provides a replicable framework for assessing lighting compatibility across heritage-sensitive environments. [1] [12] [16]

Key Contributions:

1. Methodology: First validated integration of the AHP-GIS methodology for assessing heritage-sensitive LED lamps (CR=0.07, η^2=0.445) [12] [16]
2. Empirical: The effect of colour temperature (73% dissatisfaction with 4000 K) conflicts with the optimal range of 2700–3200 K [11] [10]
3. Economic: The indicated correction costs (€125,000) justify cultural preservation over efficiency losses [7] [9]
4. Spatial: Strong predictive formal indicators revealed (street width r=0.78, proximity to UNESCO OR =4.23) [16]
5. Environmental: Demonstration of the shared biodiversity benefits of appropriate spectral selection [24]

Conclusive result: Standardised technical solutions optimised for modern, architecturally designed contexts fail when applied to traditional organic forms, where spectral mismatch (4000 K specifications) represents the most economically correct but culturally damaging implementation error.

Future Research Directions:

- Multi-site verification across similar North African heritage cities
- Longitudinal monitoring of corrected installations following Turin protocols [1]
- Integration of biodiversity monitoring with cultural satisfaction metrics [24]
- Development of culturally adapted and standardised LENI protocols [18]
- Investigation of machine learning applications for predictive assessment of formal compatibility

This research provides municipal authorities with validated tools to navigate the complex intersection of energy efficiency, cultural preservation, and technological innovation in heritage-sensitive urban lighting transitions. [6] [5]

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Acknowledgement

This research is part of a PhD project in the Department of Urban Management at the University of Mohamed Boudiaf in M'sila, Algeria. We would like to thank the municipal officials of the Municipality of Central Algiers. We would also like to thank the officials and engineers of ERMA, as well as all the experts and participants in the interviews and surveys, for their time.

Data Availability Statement

Research data supporting the conclusions are available in the supplementary materials. Additional detailed datasets are available from the corresponding author upon reasonable request.

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