

Multicriteria Decision Analysis of Heritage Preservation Alternatives



Date:
November 2025

Abstract

This study presents a participatory, multi-criteria framework for evaluating adaptive reuse alternatives of wooden heritage buildings, integrating both authenticity and sustainability dimensions. Stakeholder priorities were elicited through workshops and transformed into normalized weights using the Simos technique. Four design alternatives—Continuity, Cultivation, Differential, and Optimisation—were assessed using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), applying the derived weights to evaluate performance across cultural, social, economic, and ecological criteria. Indicator-level analyses and sensitivity tests confirmed the robustness of rankings, with the Cultivation alternative demonstrating the highest overall performance. Findings highlight the trade-offs between heritage authenticity and sustainability objectives and demonstrate how combining participatory methods with quantitative evaluation can support evidence-based decision-making for adaptive reuse. The framework is adaptable for heritage contexts globally, promoting transparency, stakeholder engagement, and sustainable heritage management.

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1 Introduction

The adaptive reuse of heritage buildings has become an important strategy to balance preserving cultural identity with promoting sustainable urban development. Historic wooden structures, in particular, represent both local craftsmanship and intangible knowledge, but they are increasingly at risk from neglect, environmental damage, and uncontrolled modernization (ICOMOS, 2013; UNESCO, 2021). The UNESCO Recommendation on the Historic Urban Landscape (2011) and the UN 2030 Agenda for Sustainable Development (Goals 11 and 12) stress the need to protect heritage through sustainable reuse, involve communities, and maintain authenticity while allowing new social and economic uses. Despite these global frameworks, many adaptive reuse projects remain dominated by expert-driven approaches that inadequately incorporate stakeholder values or intangible heritage dimensions. Previous research has highlighted that conventional cost–benefit analyses or architectural evaluations often overlook the cultural and social functions of heritage assets and rarely employ multidimensional, participatory decision-making frameworks (Hasan et al., 2019; Tu, 2020; Chang et al., 2023). Consequently, a methodological gap persists in systematically balancing authenticity, social cohesion, financial viability, and environmental performance in adaptive reuse decisions. This study aims to fill this gap by proposing a participatory co-evaluation framework that combines qualitative and quantitative factors using Multi-Criteria Decision Analysis (MCDA). The framework addresses heritage authenticity, including both material and immaterial aspects, by engaging different stakeholders to define objectives, assess options, and develop adaptive reuse solutions together. The analysis uses two main techniques: (1) the Simos weighting method (Simos, 1990; Roy & Słowiński, 2013) to convert stakeholder preferences into measurable weights, and (2) the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to evaluate how closely reuse alternatives achieve an ideal balance of sustainability and authenticity. The study followed two main phases. Phase 1 involved data collection, setting objectives, and co-design through three fieldworks (2024–2025) documenting historical layers, architectural forms, and stakeholder consultations. Two sets of objectives were identified: (i) sustainability objectives covering social, economic, and environmental dimensions, and (ii) adaptive reuse objectives focusing on authenticity, community revitalization, and material continuity. These objectives guided the creation of four reuse alternatives—Continuity,

Cultivation, Differential, and Optimisation, each reflecting a different balance between conservation and innovation.

Phase 2 applied the MCDA-TOPSIS evaluation to compare these alternatives. Using weights from the Simos method, each alternative was scored against 20 performance indicators across heritage, social, environmental, and financial dimensions. TOPSIS ranking and sensitivity analysis ($\pm 10\%$ and $\pm 20\%$ weight variations) tested the stability of the results. Visual tools such as bar plots, radar charts, heatmaps, and correlation matrices helped make the results clear and understandable for stakeholders.

This integrated framework helps bridge the gap between heritage theory and practice by combining authenticity, participation, and multidimensional sustainability in one analytical approach, supporting evidence-based decisions for adaptive reuse.

2 Objectives of the Study

The primary aim of this study is to develop a participatory, evidence-based framework for evaluating adaptive reuse alternatives of heritage buildings, integrating stakeholder preferences, sustainability criteria, and heritage authenticity considerations. The study has the following specific objectives:

2.1 To assess stakeholder preferences for adaptive reuse objectives using the Simos card-ranking method

- Gather and rank the importance of sustainability, cultural, social, and economic objectives from different stakeholder groups, including heritage officers, local communities, architects, and policy-makers.
- Convert these ordinal rankings into cardinal weights to measure the relative importance of each objective.

2.2 To evaluate and rank four heritage reuse alternatives using the TOPSIS approach based on sustainability and authenticity indicators

- Define and measure quantitative and qualitative indicators under each objective (e.g., energy efficiency, timber conservation, social inclusivity).

- Compare the four alternatives—Continuity, Cultivation, Differential, and Optimisation—against the Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS) to calculate closeness coefficients and generate preference rankings.

2.3 To test the robustness of alternative rankings through sensitivity analysis

- Simulate $\pm 10\%$ and $\pm 20\%$ changes in objective weights to examine the stability of alternative rankings.
- Identify critical objectives and indicators that most influence decision-making outcomes.

2.4 To provide evidence-based visual insights for participatory decision-making in heritage reuse projects

- Present results using dashboards, heatmaps, boxplots, and radar charts to help stakeholders easily understand the findings.
- Facilitate iterative co-evaluation and discussion to build consensus on the preferred adaptive reuse strategies.

3 Methodology

Building on the principles of heritage authenticity and the conceptual framework for adaptive reuse, this study uses a participatory and co-evaluation approach. It considers different evaluation criteria and dimensions of authenticity from the perspectives of various stakeholders.

The methodology includes two main phases. The first phase focuses on collecting historical and architectural data, setting objectives, and developing design proposals. The second phase involves comparing and evaluating the criteria and indicators with the participation of all stakeholders. In this stage, the most suitable or “ideal” solution for adaptive reuse emerges based on collective input.

This approach is iterative, dynamic, and co-evolving. It involves stakeholders at every step—from defining objectives to selecting and validating the final reuse option. The process encourages continuous feedback and shared learning, helping to improve decision-making

and co-design. In the end, it leads to a solution that reflects collective reflection and collaboration, supported by systematic evaluation tools.

3.1 Phase 1: Data Collection, Objective Selection, and Design Proposal

The main purpose of this phase is to collect historical and architectural data for the abandoned building, set sustainability and adaptive reuse objectives, and guide the co-design process. Two sets of objectives were considered: (1) objectives that align with sustainability standards and (2) specific objectives related to the adaptive reuse of the building. Based on these, the phase was organized into four main parts.

3.1.1 Building Data Collection

This step focused on collecting and analyzing detailed information about the building's relics targeted for adaptive reuse. Three field missions were conducted between 2024 and 2025.

Two main types of data were gathered:

- **Historical data:** to understand the building's chronological development, historical layers, and cultural significance.
- **Architectural data:** to document the building's geometric form, morphology, and spatial composition.

Data collection methods included key informant interviews, archival research, and manual measurements. These approaches ensured accurate mapping of the building's physical characteristics and heritage value.

3.1.2 Definition of Adaptive Reuse Objectives and Criteria

After collecting the historical and architectural data, the first stakeholder meeting was held to define the objectives and criteria for the building's adaptive reuse. Two main sets of objectives were developed: sustainability objectives and specific adaptive reuse objectives. The **sustainability objectives** were drawn from a literature review and aligned with the three pillars of sustainable development—social, economic, and environmental sustainability. These served as the foundation for discussion with stakeholders. The **specific adaptive reuse objectives** focused on the cultural, historical, and functional transformation of the building.

All objectives were expressed qualitatively to support creativity and open reflection during the co-design process. This participatory approach encouraged stakeholders and professionals to explore ideas together, promoting reflection, adaptation, and innovation. Through this process, initial ideas were refined into more concrete adaptive reuse solutions that better addressed community and generational needs.

Table 1. Objectives, criteria, indicators and evaluation scales for adaptive re-use of abandoned and dilapidated wooden heritage.

<i>Dimension</i>	<i>Objective (No.)</i>	<i>Criteria (ID)</i>	<i>Indicator description</i>	<i>Evaluation scale</i>
<i>Heritage Continuity</i>	1. Safeguard and transmit the authenticity of wooden and zinc fabric	1.1 Structural soundness of timber	1.1.1 Share of primary timber members (posts, beams, trusses) retained after intervention	Cardinal (%) of original building material retained
			1.1.2 The existing functional characteristics of the wooden members are retained	Cardinal (%) of original building material characteristics retained
	2. Revitalize knowledge of local wooden-building traditions	1.2 Functional compatibility with heritage values	1.2.1 Compatibility of new uses with character-defining wooden features (joinery, finishes, spatial order)	Ordinal (5-point expert panel)
			2.1 Community heritage literacy	2.1.1 Participation rate in heritage walks, talks, or carpentry demonstrations linked to the project
3. Valorize intangible carpentry heritage	3.1 Narrative interpretation and storytelling	3.1.1 Quality and depth of interpretation of timber craft (exhibits, signage, digital media)	Ordinal (5-point expert panel)	
<i>Social Cohesion</i>	4. Strengthen social capital through reuse	4.1 Inclusivity breadth	4.1.1 Diversity of user groups (age, gender, ability) engaged in building construction	Cardinal (% diversity index) / Ordinal (5-point expert panel)
		4.2 Neighbourhood activation	4.2.1 Activation of community activities in the building construction process and building usage	Ordinal (5-point expert panel)
		4.3 Co-creation intensity	4.3.1 Stakeholders acting as co-producers (community orgs, artisans, schools)	Ordinal (5-point expert panel)
<i>Circular & Creative Economy</i>	5. Stimulate local wood-based entrepreneurship	5.1 Job creation	5.1.1 Direct jobs created by the adaptive re-use (operation + maintenance + monitoring)	Cardinal (number of jobs)

<i>Access & Environmental Resilience</i>		5.2 Leveraged local co-financing	5.2.1 Ratio of local/private contributions to total project cost	Local contribution (in Euros)
	6. Financially Viability	6.1 Economic value of proposal	6.2 Financial sufficiency and returns	Economic value (in Euros)
		6.1.1 Net Cost of Restoration	6.2.1 Payback period	In number of years
	7. Improve universal access and urban connectivity	7.1 Physical and urban accessibility	7.1.1 Accessibility of interior and public interface (ramps, lifts, wayfinding; compliance with standards)	Ordinal (5-point expert panel)
	8. Increase operational energy self-reliance	8.1 Energy self-sufficiency & demand reduction	8.1.1 Share of annual electricity from on-site renewables or renewable PPAs	Ordinal (5-point expert panel)
			8.1.2 Reduction of final energy use versus pre-intervention baseline	Cardinal (kWh/m ² ·yr) / Ordinal (5-point expert panel)
	9. Reduce resource consumption and environmental impacts	9.1 Water efficiency	9.1.1 Reduction in potable water use via recovery/reuse systems	Cardinal (% reduction)
		9.2 Bio-/nature-based components	9.2.1 Area of green roofs/walls, rain gardens, or permeable vegetated surfaces delivered	Cardinal (m ²)
		9.3 Timber reuse & waste avoidance	9.3.1 Mass of construction/demolition waste avoided through salvage and reuse of wood	Ordinal (5-point expert panel)
		9.4 Life-cycle carbon reduction	9.4.1 Reduction in whole-life GHG emissions compared with a code-compliant new build	Cardinal (kgCO ₂ e/m ² or %)
10. Regenerate biocultural assets	10.1 Habitat and urban biodiversity	10.1.1 Area of new/restored habitat and biocultural features (e.g., bat boxes, native planting)	Cardinal (m ²)	

To improve the clarity and readability of visual outputs, abbreviated forms of indicator names were used in plots and graphical representations. For transparency and consistency, Table 2 provides a complete mapping of these abbreviated labels to their full indicator descriptions as applied in the analysis.

Table 2. Mapping of Full Indicator Descriptions to Short Labels Used in Figures

No.	Full Indicator Description	Short Label (Used in Figures)
1.1.1	Share of primary timber members (posts, beams, trusses) retained after intervention	Timber retained
1.1.2	The existing functional characteristics of the wooden members are retained	Wood function
1.2.1	Compatibility of new uses with character-defining wooden features (joinery, finishes, spatial order)	Feature compatibility
2.1.1	Participation rate in carpentry demonstrations linked to the proposal	Carpentry participation
3.1.1	Quality and depth of interpretation of timber craft (through restoration and new construction)	Craft interpretation
4.1.1	Diversity of user groups (age, gender, ability) engaged in building construction	User diversity
4.2.1	Activation of community activities in the building construction process	Community activation
4.3.1	Stakeholders acting as co-producers (community orgs, artisans, schools)	Co-production
5.1.1	Direct jobs created by the adaptive re-use (operation + maintenance + monitoring)	Jobs created
5.2.1	Ratio of local/private contributions to total project cost	Local contribution
6.1.1	Net cost of restoration	Restoration cost
6.2.1	Payback period	Payback period
7.1.1	Accessibility of interior and public interface (ramps, lifts, wayfinding; compliance with standards)	Accessibility
8.1.1	Share of annual electricity from on-site renewables or renewable PPAs	Renewable energy share
8.1.2	Reduction of final energy use versus pre-intervention baseline	Energy reduction
9.1.1	Reduction in potable water use via recovery/reuse systems	Water reduction
9.2.1	Area of green roofs/walls, rain gardens, or permeable vegetated surfaces delivered	Green surfaces
9.3.1	Mass of construction/demolition waste avoided through salvage and reuse of wood	Waste reduction
9.4.1	Reduction in whole-life GHG emissions compared with a code-compliant new building	GHG reduction
10.1.1	Area of new/restored habitat and biocultural features (e.g., bat boxes, native planting)	Habitat restored

3.1.3 Prioritization of Objectives

To prioritize the objectives, two rounds of questionnaires were conducted with 45 diverse local stakeholders. The participants included heritage officers, policymakers, descendant families, community representatives, organized interest groups, and professional architects. During these rounds, ten main objectives, along with eighteen criteria and twenty indicators, were identified. These elements were designed both to guide the formulation of adaptive

reuse alternatives and to support their evaluation. The criteria were presented and discussed during public consultations to ensure a shared understanding among participants. Stakeholders were then asked to rank the objectives on a scale from 10 to 1, where 10 represented the most important objective and 1 the least important. To convert these rankings into measurable weights, the **Simos method** (Simos, 1990; Roy & Słowiński, 2013) was applied. This four-step card-based technique transformed the ordinal preferences into cardinal weights, providing an objective representation of stakeholder priorities for use in the next phase of analysis.

3.1.4 Development of Architectural Alternatives

Based on the prioritized objectives, four adaptive reuse design proposals were developed. Each reflects a different architectural and cultural approach while balancing authenticity and functionality:

- **Differential (new prevailing over old):** In this approach, new architectural elements dominate while preserving parts of the historic structure. Half of the building was redesigned in glass, and the remaining original elements were maintained. The building was proposed as an empty tourist site, clearly distinguishing the new from the old.
- **Continuity (minimal intervention):** This proposal involves minimal restoration to preserve the building's 1956 outlook. The building retains its original function as a family house for the descendant community and the Ekpo Abasi Royal House.
- **Cultivation (stratified dialogue):** This approach layers historical narratives, reflecting the 1886 architectural form before later modifications. The building is adapted as a community museum and library, allowing the history to remain visible and interactive.
- **Optimization (idealized restoration):** Here, the historic architecture is reinterpreted using modern materials. The proposal creates a contemporary museum while symbolically preserving the building's heritage story. The material itself is secondary to the historical narrative.

Each alternative offers a unique pathway for adaptive reuse, demonstrating different balances between cultural authenticity, functionality, and sustainability.

3.1.5 Development of Project Sustainability and Sensitivity Indicators

To evaluate the sustainability of each design alternative, four indicators were developed:

1. **Ecological friendliness**
2. **Cultural sensitivity**
3. **Social viability**
4. **Economic feasibility**

A sensitivity analysis was conducted using these indicators. This analysis assessed how well each alternative met sustainability objectives and identified which features were most or least vulnerable to change. Comparing the alternatives in this way provided a multidimensional understanding of how each design aligned with sustainability and authenticity goals, highlighting key characteristics essential for the success of the adaptive reuse proposals.

Table 3. Mapping of sustainability dimensions, indicator categories, and calculation guidance for multidimensional analysis

<i>Sustainability</i>	<i>Categories / factors / themes</i>	<i>Indicators</i>
<i>Economic feasibility</i>	Financial viability & business model	1.1 Project net present value (NPV) *(cost criterion) *
		1.2 Payback period *(cost criterion) *
	Market activation & mixed-use intensity	1.3 Annual revenue diversification index
	Local value chains & procurement	1.4 Share of spend to local timber/heritage SMEs
	Employment & enterprise	1.5 Direct jobs created (operation + heritage programming)
	Risk & financial resilience	1.6 Debt-service coverage ratio (DSCR)
<i>Ecological friendliness</i>	Energy performance of timber building	2.1 Reduction in final energy use vs. pre-intervention *(cost criterion) *
	On-site renewables / self-sufficiency	2.2 Share of annual electricity from renewables
	Timber conservation & fabric retention	2.3 Percentage of primary timber members retained

	Material circularity (wood salvage & reuse)	2.4 Mass of salvaged timber reused on site
	Construction & demolition waste diverted	2.5 C&D waste diversion rate
	Water performance	2.6 Potable water reduction via reuse/recovery
	Whole-life carbon	2.7 Life-cycle GHG emissions *(cost criterion) *
	Nature-based solutions & biodiversity	2.8 New/rehabilitated green area and habitat features
<i>Social viability</i>	Inclusion & equitable access	3.1 Diversity of users/beneficiaries
	Health, safety & comfort	3.2 post-occupancy comfort and perceived safety
	Accessibility & connectivity	3.3 Universal access compliance
	Community engagement & co-production	3.4 Stakeholders acting as co-producers
	Education & skills	3.5 Heritage carpentry apprenticeships/training
	Place activation & social vibrancy	3.6 Footfall/dwell-time uplift in the block
<i>Cultural sensitivity</i>	Material authenticity of wooden fabric	4.1 Compatibility of interventions with character-defining timber features
	Intangible heritage & craft continuity	4.2 Depth/quality of interpretation of carpentry traditions
	Reversibility & minimal intervention	4.3 Proportion of reversible additions
	Fit-for-purpose (use–heritage coherence)	4.4 Functional compatibility score

3.2 Phase 2: Evaluation and Selection of Optimal Solution Using MCDA

After defining the adaptive reuse objectives, developing four architectural alternatives, and establishing evaluation indicators in Phase 1, Phase 2 focuses on the systematic evaluation and selection of the optimal adaptive reuse solution using a Multi-Criteria Decision Analysis (MCDA) approach. This phase is critical, as it integrates stakeholder perceptions of heritage authenticity with sustainability, social, cultural, and economic objectives, ensuring participatory, evidence-based, and robust decision-making.

3.2.1 Multicriteria Evaluation

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Hwang & Yoon, 1981) was chosen for the evaluation because it:

- Allows integration of qualitative and quantitative data, critical in early phases where design alternatives may be conceptual or partially defined.
- Evaluates alternatives based on their closeness to the Positive Ideal Solution (PIS) and distance from the Negative Ideal Solution (NIS), capturing both opportunity and risk (Yoon, 1980; Balioti et al., 2018).
- Facilitates stakeholder participation through weighted criteria derived from the Simos card-ranking method (Simos, 1990; Roy & Słowiński, 2013).
- Offers a transparent, efficient, and easily interpretable framework suitable for iterative co-evaluation.
- Is adaptable: additional alternatives or indicators can be incorporated without changing the underlying procedure (Pinzon Amorocho & Hartmann, 2022).

3.2.2 Order of Preference by Similarity to Ideal Solution (TOPSIS) Evaluation Steps

3.2.2.1 Performance Matrix

Each alternative (Differential, Continuity, Cultivation, Optimisation) was evaluated against the criteria and indicators established in Phase 1. Qualitative criteria were converted into numerical scores using stakeholder judgment.

3.2.2.2 Normalization of Decision Matrix

To make values comparable across different scales:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}}$$

Where:

- r_{ij} = normalized value of alternative i for criterion j
- x_{ij} = original performance score
- m = number of alternatives

3.2.2.3 Weighted Normalized Matrix

Weights were assigned to criteria using the **Simos weighting method**¹, which converts stakeholder ordinal rankings into cardinal weights. If w_j is the weight of criterion j , the weighted normalized score is:

$$v_{ij} = w_j \cdot r_{ij}$$

Step 4: Identify Positive and Negative Ideal Solutions

$$A^+ = \{v_1^+, v_2^+, \dots, v_n^+\}, v_j^+ = \max(v_{ij})$$

$$A^- = \{v_1^-, v_2^-, \dots, v_n^-\}, v_j^- = \min(v_{ij})$$

Step 5: Euclidean Distance from Ideal Solutions

$$S_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2}, S_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2}$$

Step 6: Closeness Coefficient and Ranking

$$CC_i = \frac{S_i^-}{S_i^+ + S_i^-}, 0 \leq CC_i \leq 1$$

Where CC_i = relative closeness to the ideal solution. Alternatives are ranked based on decreasing CC_i , with higher values indicating preferred solutions.

¹ The Simos method (Simos, 1990) uses a card-ranking procedure to translate stakeholder ordinal preferences into numerical weights, enabling transparent and participatory assignment of importance to objectives.

3.2.3 Scenario Evaluation: Sensitivity Analysis

To assess the robustness of rankings:

- **Weights Adjustment:** Criterion weights were varied systematically ($\pm 10\text{--}20\%$) to reflect potential subjectivity and uncertainty.
- **Ranking Recalculation:** TOPSIS was re-applied to evaluate changes in alternative preference order.
- **Outcome:** Identified critical criteria influencing rankings and assessed stability of results, ensuring a robust, participatory evaluation.

3.2.4 Stakeholder Validation and Participatory Decision-Making

Following the TOPSIS ranking and sensitivity analysis:

- Stakeholders reviewed the alternative rankings in a **co-design workshop**, reflecting on trade-offs between authenticity, sustainability, and functional objectives.
- Iterative feedback allowed refinement of criteria, weights, and final selection, enhancing social acceptance and legitimacy of the chosen adaptive reuse solution.

3.2.5 Rationale for Choosing TOPSIS

The TOPSIS method was selected for this study because it effectively supports the evaluation of multiple adaptive reuse alternatives across diverse criteria. It combines quantitative and qualitative information, allows stakeholder participation, and produces clear, reproducible results. Its flexibility and simplicity make it particularly suitable for participatory, evidence-based decision-making in heritage reuse projects.

- **Multidimensional evaluation:** Supports integration of multiple criteria (cultural, social, economic, environmental).
- **Qualitative and quantitative inclusion:** Captures both early conceptual ideas and later detailed project data.
- **Transparency and participation:** Weights can be derived from stakeholders; results are clear and reproducible.
- **Iterative adaptability:** New alternatives or indicators can be integrated without changing the workflow.
- **Mathematical simplicity:** Euclidean distance-based calculation is simple, easy to understand, and facilitates robust decision-making.

4 Results

The analyses in this study systematically evaluated adaptive reuse alternatives for heritage buildings by integrating stakeholder priorities, sustainability criteria, and authenticity objectives. The Simos method was used to quantify the relative importance of each objective, while the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) ranked the reuse alternatives based on these weighted criteria. The comparison between analytical results and stakeholder preferences validated the consistency between perceived and calculated outcomes. Finally, a sensitivity analysis tested the robustness of the rankings. Together, these steps created a transparent, participatory, and evidence-based framework for decision-making in heritage building reuse.

4.1 Weight Derivation (Simos Output)

To capture stakeholder priorities in heritage adaptive reuse, the Simos method was applied. This participatory card-ranking technique transforms ordinal rankings provided by stakeholders into normalized cardinal weights, enabling quantitative integration into the subsequent multi-criteria decision analysis (Simos, 1990; Roy & Słowiński, 2013).

Stakeholder Engagement

A total of 45 stakeholders participated in the weighting process, including heritage officers, local community representatives, policymakers, architects, and interest groups. Each participant ranked ten key objectives on a scale from 1 (lowest) to 10 (highest) according to their perceived importance. This participatory approach ensured that both tangible (e.g., structural integrity, financial viability) and intangible (e.g., traditional craftsmanship, community engagement) aspects of heritage preservation were adequately reflected. The ordinal rankings were subsequently converted into normalized cardinal weights through the Simos procedure for use in the TOPSIS analysis.

Contribution to Study Objectives:

- Establishes a transparent and participatory weighting framework for multi-criteria evaluation.
- Ensures that sustainability, cultural, social, and economic objectives are quantitatively integrated into the TOPSIS ranking.

- Supports the overall study aim of balancing authenticity and sustainability in heritage reuse decisions.

Figure 1. Objectives Scores Derived from the Simos Method

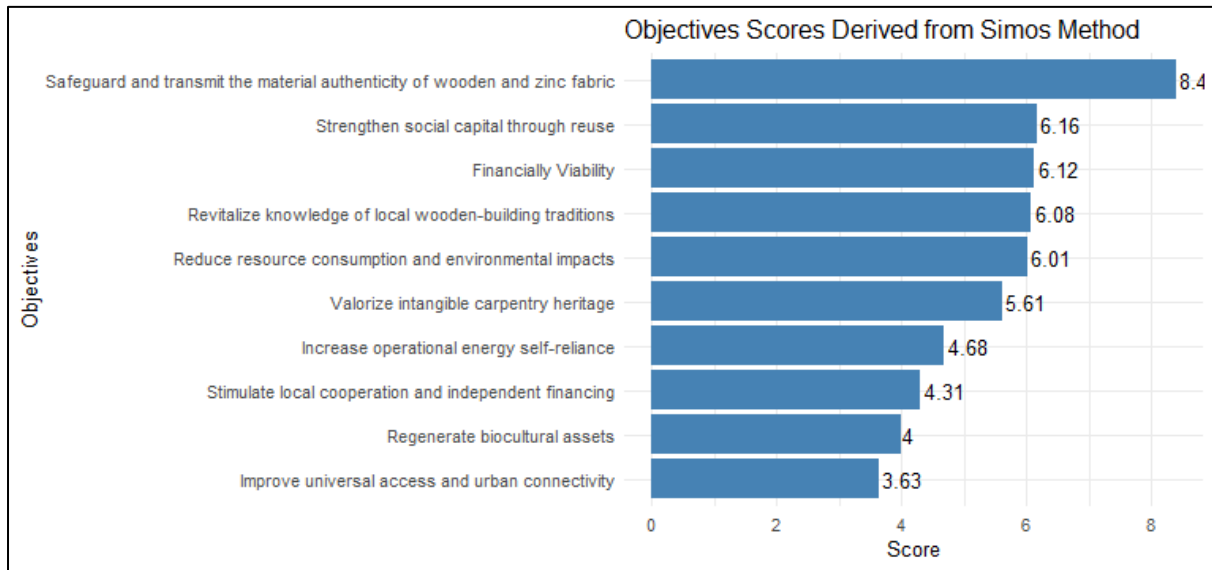


Figure 1, Visualizes raw stakeholder scores for each objective prior to normalization, illustrating initial perceptions of importance.

Calculation of Weights:

The Simos procedure followed four structured steps:

- Card Ordering:** Stakeholders arranged objectives from least to most important.
- Equal Gaps:** Spacing between cards represented perceived differences in importance.
- Card Counting:** Scores were aggregated across participants.
- Normalization:** Aggregated scores were standardized so total weights summed to one, making them suitable for the subsequent multi-criteria decision analysis (MCDA).

Table 4. Table 4.1. Normalized Weights of the Ten Objectives Derived from the Simos Method

Objective	Score	Weight
1. Safeguard and transmit the material authenticity of wooden and zinc fabric	8.40	0.153
2. Revitalize knowledge of local wooden-building traditions	6.08	0.111
3. Valorize intangible carpentry heritage	5.61	0.102
4. Strengthen social capital through reuse	6.16	0.112
5. Stimulate local cooperation and independent financing	4.31	0.078
6. Financial Viability	6.12	0.111
7. Improve universal access and urban connectivity	3.63	0.066
8. Increase operational energy self-reliance	4.68	0.085

9. Reduce resource consumption and environmental impacts	6.01	0.109
10. Regenerate biocultural assets	4.00	0.073

The normalized weights presented in Table 4.1 were then used in the TOPSIS evaluation to rank adaptive reuse alternatives (see Figure 2). This progression—from stakeholder scoring to normalized weighting and visualization—provides a logical and transparent analytical flow.

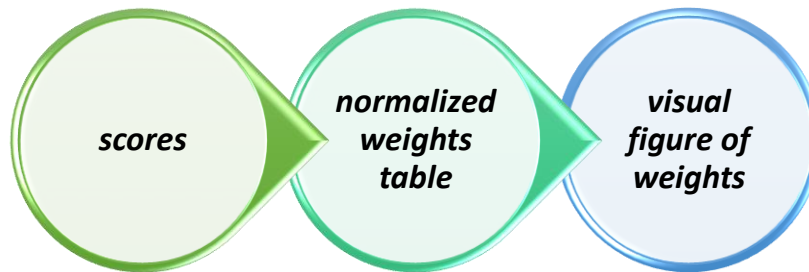
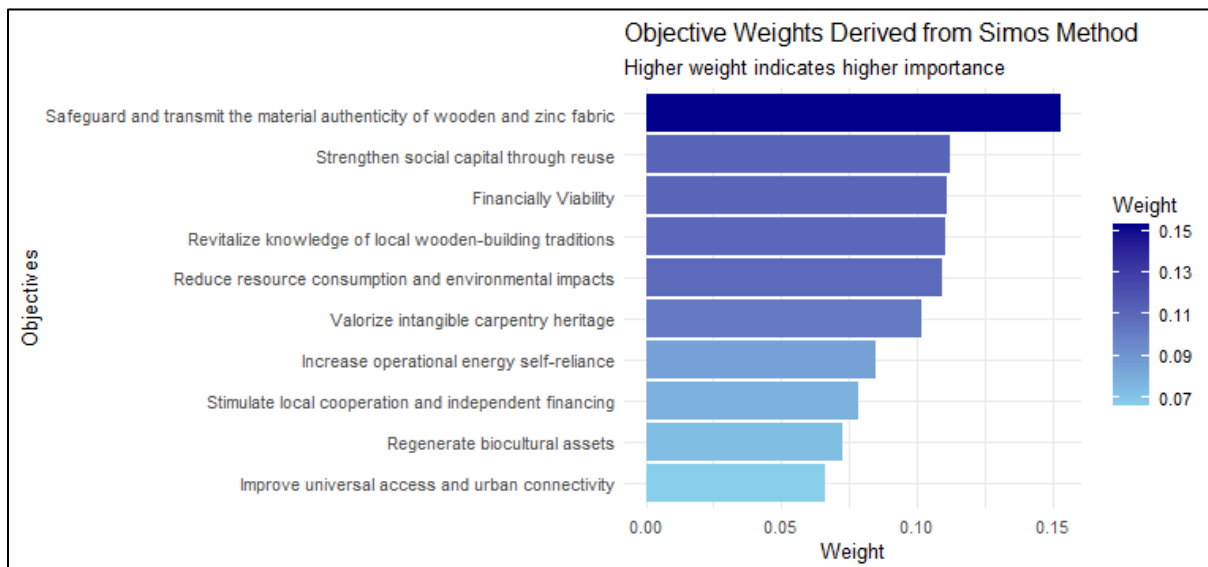


Figure 2. Objective Weights Derived from the Simos Method



The results show that “Safeguard and transmit the material authenticity” emerged as the most critical objective, with the highest weight (0.153), underscoring stakeholders’ commitment to preserving the physical integrity of heritage materials. Socially oriented objectives, including “strengthening social capital” and “revitalizing local carpentry knowledge,” also received substantial weights, reflecting a recognition of community identity and intangible heritage values. Financial and environmental objectives were

moderately weighted, suggesting a balanced consideration of economic and sustainability priorities. The lowest weight was assigned to “regenerating biocultural assets,” implying that while ecological regeneration was valued, it was perceived as a secondary concern in the immediate reuse context.

These weights form the quantitative foundation for the subsequent TOPSIS evaluation, ensuring that the final ranking of reuse alternatives is grounded in stakeholder-informed priorities across cultural, social, and sustainability dimensions.

4.2 TOPSIS Evaluation Results

The four proposed adaptive reuse alternatives—Continuity, Cultivation, Differential, and Optimisation—were evaluated using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method. The analysis incorporated the weighted objectives derived from the Simos procedure (see Section 4.1). TOPSIS enables multi-criteria evaluation by determining each alternative’s distance from the **Positive Ideal Solution (PIS)** and the **Negative Ideal Solution (NIS)**. From these distances, a **Closeness Coefficient (CC)** is calculated, representing the degree to which each alternative approximates the ideal solution. A higher CC value indicates stronger alignment with desired objectives across sustainability and authenticity dimensions.

Contribution to Study Objectives

- Identifies the most suitable adaptive reuse alternative that balances authenticity, sustainability, and stakeholder preferences.
- Provides quantitative evidence to support transparent, data-driven decision-making.
- Demonstrates how alternatives perform in maximizing sustainability outcomes while preserving cultural and architectural heritage value.

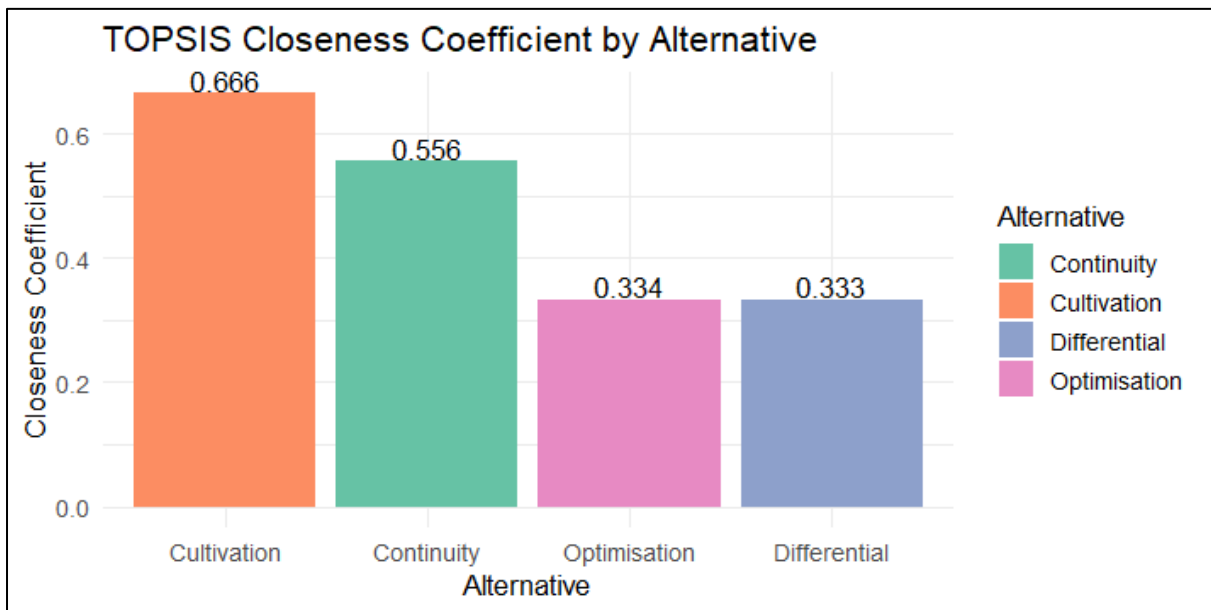
Table 5. TOPSIS Evaluation Results by Alternative

<i>Alternative</i>	<i>S⁺ (Distance to PIS)²</i>	<i>S⁻ (Distance to NIS)</i>	<i>Closeness Coefficient (CC)</i>	<i>Rank</i>
<i>Continuity</i>	0.1675	0.2097	0.5560	2
<i>Cultivation</i>	0.1331	0.2656	0.6662	1
<i>Differential</i>	0.2589	0.1294	0.3332	4

² S⁺ and S⁻ represent the Euclidean distances of each alternative from the Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS), respectively (Hwang & Yoon, 1981, “Multiple Attribute Decision Making: Methods and Applications,” Springer).

Table 5. presents the results of the TOPSIS evaluation, including the computed distances to the PIS and NIS, corresponding CC values, and the final ranking of the four alternatives. As shown in Table 5, **Cultivation** achieved the highest CC value (0.6662), indicating the closest alignment with the ideal sustainability and authenticity objectives. **Continuity** followed with a moderate CC value (0.5560), while **Optimisation** and **Differential** scored lower (0.3338 and 0.3332, respectively), suggesting comparatively weaker performance. These findings imply that Cultivation most effectively balances environmental efficiency, community engagement, and cultural preservation.

Figure 3. TOPSIS Closeness Coefficient by Alternative



This figure visualizes the CC values for each adaptive reuse alternative, highlighting **Cultivation** as the most preferred and **Differential** as the least favored option.

4.2.1 Comparison of TOPSIS Scores and Stakeholder Preferences

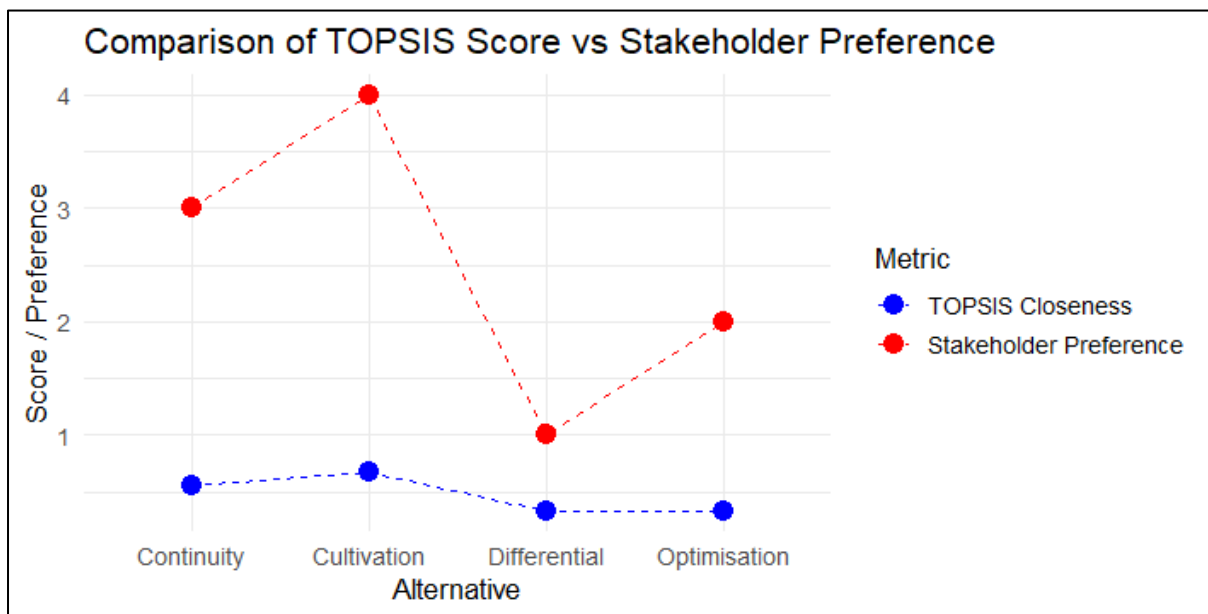
To validate the analytical outcomes, a comparison was conducted between the TOPSIS-derived CC scores and stakeholder preference rankings. The stakeholder rankings were rescaled to ensure direct comparability, where higher values represent stronger preference. This comparison provides an additional layer of verification to assess whether the quantitative evaluation aligns with perceived stakeholder priorities.

To validate the analytical outcomes, a comparison was conducted between the TOPSIS-derived closeness coefficient (CC) scores and stakeholder preference rankings. The stakeholder rankings were rescaled to ensure direct comparability, where higher values represent stronger preference. This comparison serves to determine the degree of alignment between the TOPSIS results and stakeholder expectations, providing an additional layer of verification to assess whether stakeholder values are accurately reflected in the multi-criteria decision-making process.

Contribution to Study Objectives:

- Reinforces that the evaluation framework incorporates participatory input and reflects socially acceptable outcomes.
- Demonstrates that technical assessments and community perceptions converge, enhancing legitimacy and transparency in adaptive reuse decision-making.

Figure 4. Comparison of TOPSIS Scores and Stakeholder Preferences



The comparative results indicate a strong agreement between stakeholder preferences and TOPSIS outcomes. Both ranked **Cultivation** as the most preferred alternative, followed by **Continuity**, **Optimisation**, and **Differential**, respectively. This consistency confirms that stakeholder perceptions align closely with the quantitative evaluation, validating the robustness and participatory relevance of the assessment framework.

4.3 Sensitivity Analysis

To assess the robustness of the TOPSIS evaluation, a sensitivity analysis was conducted by perturbing the objective weights by $\pm 10\%$ and $\pm 20\%$ from their original Simos-derived values. This step aimed to test whether small changes in stakeholder-assigned priorities would significantly influence the ranking of adaptive reuse alternatives. Sensitivity analysis serves two key purposes: (a) to verify the stability of the multi-criteria decision results under varying weight assumptions and (b) to confirm that stakeholder-driven preferences do not overly bias the final ranking outcomes.

This procedure contributes to the study’s objectives by providing a quantitative measure of decision reliability. Specifically, it demonstrates whether *Cultivation*—the top-ranked alternative in the baseline scenario—maintains its leading position when input weights fluctuate. Such stability enhances confidence in the methodological transparency and practical reliability of the proposed framework for heritage reuse planning.

Table 6 presents the closeness coefficients for all four alternatives across five weight perturbation levels (-20% , -10% , 0% , $+10\%$, and $+20\%$). The results reveal that *Cultivation* consistently achieved the highest closeness coefficient across all scenarios, followed by *Continuity*, while *Differential* and *Optimisation* remained the lowest-ranked alternatives. These results confirm that the ranking pattern remains unchanged even under moderate variations in stakeholder priorities.

Table 6. Sensitivity Analysis of TOPSIS Closeness Coefficient under Weight Perturbation

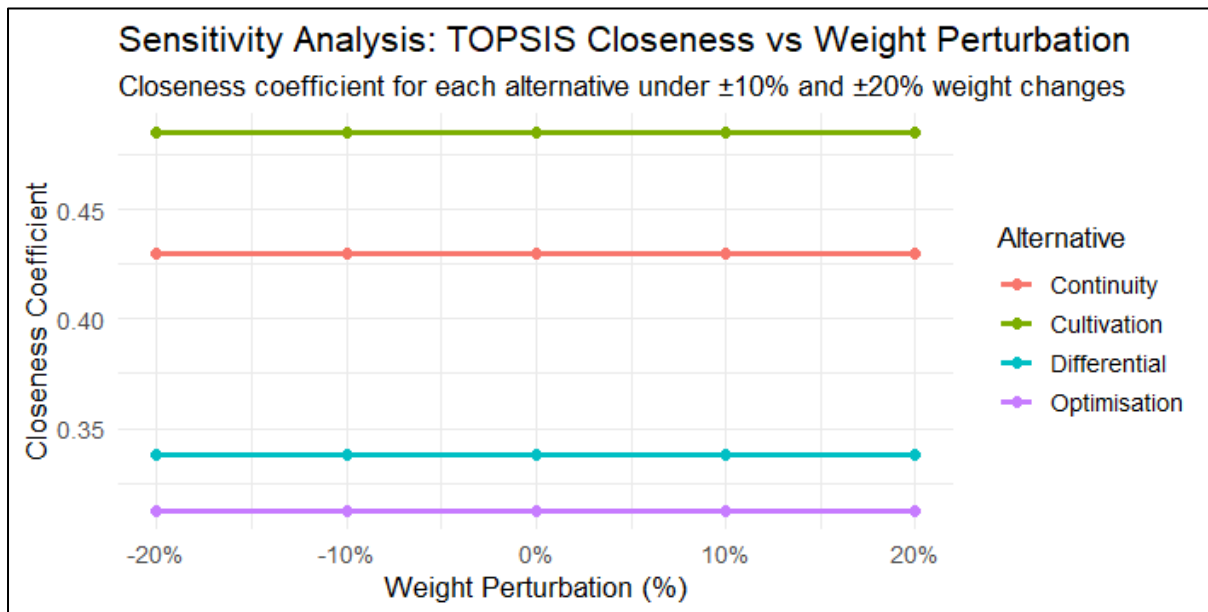
<i>Perturbation</i>	<i>Continuity</i>	<i>Cultivation</i>	<i>Differential</i>	<i>Optimisation</i>
-20%	0.4300	0.4851	0.3381	0.3124
-10%	0.4300	0.4851	0.3381	0.3124
0%	0.4300	0.4851	0.3381	0.3124
10%	0.4300	0.4851	0.3381	0.3124
20%	0.4300	0.4851	0.3381	0.3124

Table 6. shows Closeness coefficients for each alternative under $\pm 10\%$ and $\pm 20\%$ perturbation of objective weights.

Figure 5. illustrates the consistency of rankings under these perturbations. The line plot demonstrates minimal fluctuation in the closeness coefficients across all perturbation levels, confirming the robustness of the multi-criteria decision-making (MCDM) results. *Cultivation*

remains the highest-performing alternative in every case, underscoring its strong balance between sustainability and authenticity objectives.

Figure 5. Sensitivity Analysis: TOPSIS Closeness vs Weight Perturbation



The line plot demonstrates that rankings are stable across $\pm 20\%$ weight variations, confirming the robustness of the MCDA results. Cultivation remains the top-ranked alternative in all scenarios, highlighting its superior performance across sustainability and authenticity criteria.

Additional Observations

Indicator Influence: Across all alternatives, *Cultural Sensitivity* and *Ecological Friendliness* were the most influential indicators, contributing substantially to the closeness coefficients.

Literature Support: Similar robustness patterns have been reported in heritage reuse studies, where *cultural authenticity* and *participatory engagement* emerged as dominant decision factors (Bullen & Love, 2011; Shipley et al., 2006).

Practical Implication: The stability of results under varying conditions confirms that the integrated *Simos–TOPSIS* approach provides a transparent, participatory, and replicable framework for evaluating heritage building reuse alternatives.

4.4 Indicator-Level Weighted Performance by Alternative

This section decomposes each adaptive reuse alternative’s overall performance into **indicator-level weighted scores**, directly linking quantitative outcomes to the project’s ten strategic objectives. By examining each indicator’s contribution, the analysis identifies the **technical, social, and environmental factors** that most strongly influence sustainability and authenticity outcomes.

The objective of this analysis is to **enhance transparency** in how individual criteria contribute to the overall ranking and to strengthen the evidence base for **adaptive reuse strategies** that balance material authenticity, community participation, and resource efficiency.

Each indicator’s assigned weight was multiplied by its corresponding performance score to generate a weighted contribution. These were then aggregated within each alternative to form the input for the TOPSIS evaluation described in Section 4.2. This approach follows the logic of **multi-criteria performance normalization** widely applied in heritage sustainability assessments.

Table 7 presents the normalized and weighted performance of each indicator across the four adaptive reuse alternatives — Continuity, Cultivation, Differential, and Optimisation.

Table 7. Weighted Indicator-Level Performance by Alternative

<i>Indicator No.</i>	<i>Indicator Name</i>	<i>Continuity</i>	<i>Cultivation</i>	<i>Differential</i>	<i>Optimisation</i>
1.1.1	Share of primary timber members (posts, beams, trusses) retained after intervention	0.1	0.1	0.04	0.03
1.1.2	The existing functional characteristics of the wooden members are retained	0.1	0.1	0.04	0.04
1.2.1	Compatibility of new uses with character-defining wooden features (joinery, finishes, spatial order)	0.09	0.11	0.04	0.04
2.1.1	Participation rate in carpentry demonstrations linked to the proposal	0.07	0.08	0.02	0.02
3.1.1	Quality and depth of interpretation of timber craft (through restoration and new construction)	0.06	0.08	0.02	0.02
4.1.1	Diversity of user groups (age, gender, ability) engaged in building construction	0.08	0.08	0.02	0.02
4.2.1	Activation of community activities in the building construction process	0.08	0.08	0.02	0

4.3.1	Stakeholders acting as co-producers (community orgs, artisans, schools)	0.08	0.08	0.02	0.02
5.1.1	Direct jobs created by the adaptive re-use (operation + maintenance + monitoring)	0.04	0.06	0.01	0.01
5.2.1	Ratio of local/private contributions to total project cost	0.04	0.07	0	0
6.1.1	Net Cost of Restoration	0.09	0.11	0.03	0.02
6.2.1	Payback period	0.07	0.11	0.01	0.01
7.1.1	Accessibility of interior and public interface (ramps, lifts, wayfinding; compliance with standards)	0.04	0.04	0.02	0.02
8.1.1	Share of annual electricity from on-site renewables or renewable PPAs	0.06	0.06	0	0
8.1.2	Reduction of final energy use versus pre-intervention baseline	0	0	0	0
9.1.1	Reduction in potable water use via recovery/reuse systems	0	0	0	0
9.2.1	Area of green roofs/walls, rain gardens, or permeable vegetated surfaces delivered	0	0.11	0	0
9.3.1	Mass of construction/demolition waste avoided through salvage and reuse of wood	0.08	0.08	0	0
9.4.1	Reduction in whole-life GHG emissions compared with a code-compliant new building	0	0	0	0
10.1.1	Area of new/restored habitat and biocultural features (e.g., bat boxes, native planting)	0	0.07	0	0

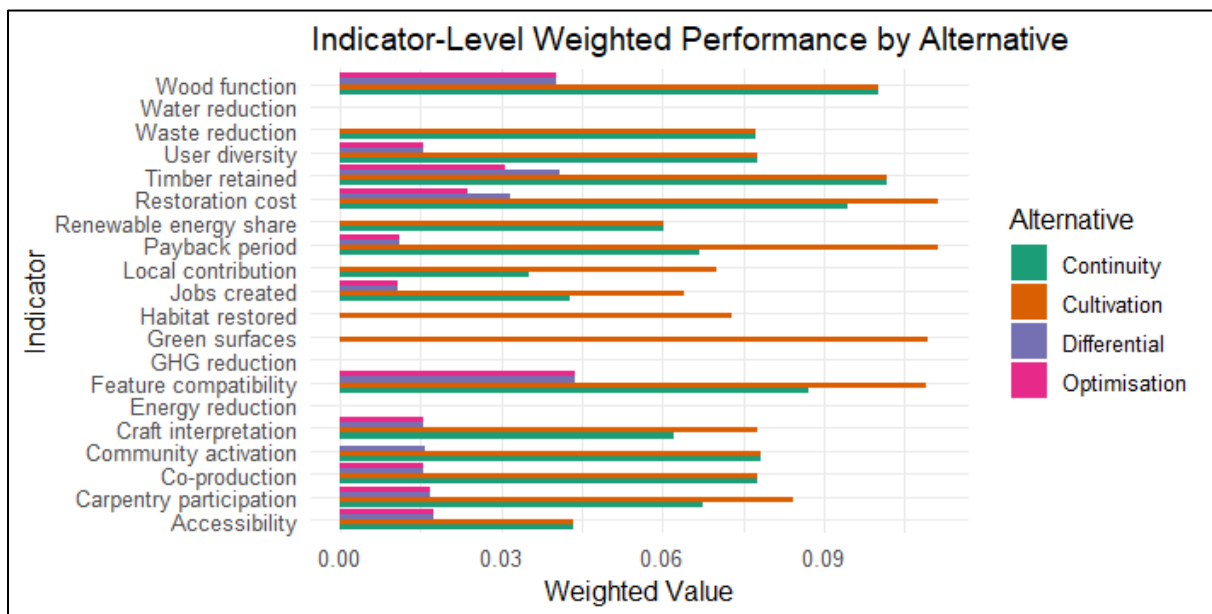
The indicator-level analysis demonstrates that the *Cultivation* alternative consistently achieves the highest cumulative weighted scores, particularly for indicators related to financial viability, such as net cost of restoration and payback period, as well as environmental design, including green infrastructure area. This suggests that *Cultivation* offers an integrated approach in which new uses enhance both material conservation and environmental adaptation.

In contrast, *Continuity* performs strongly in indicators associated with authentic material retention, reflecting its emphasis on safeguarding original wooden and zinc components. The *Differential* and *Optimisation* alternatives exhibit comparatively lower scores across most dimensions, particularly for renewable energy and water reuse indicators, indicating limited contributions to sustainability and operational efficiency. Indicators such as the retention of primary timber members demonstrate the greatest influence on overall

performance, aligning with international heritage conservation guidance that prioritizes material integrity (ICOMOS, 2013). The presence of zero-weighted indicators, including energy reduction, potable water reuse, and whole-life greenhouse gas reduction, highlights areas where data gaps or limited sustainability integration exist, suggesting opportunities for improvement in future design iterations.

Overall, this disaggregated analysis clarifies the contribution of individual technical, social, and environmental indicators to the adaptive reuse evaluation, enhancing transparency and supporting evidence-based decision-making within the TOPSIS framework.

Figure 6. Indicator-Level Weighted Performance by Alternative

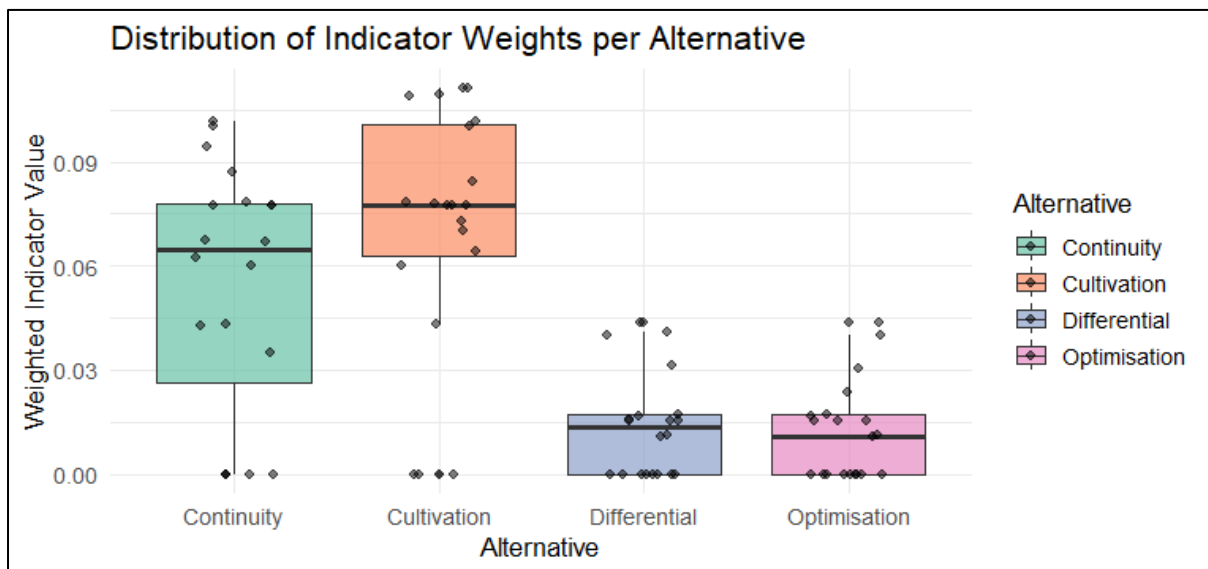


This figure visually contrasts the weighted indicator contributions across the four alternatives, enabling rapid identification of strengths and weaknesses in sustainability and authenticity dimensions.

4.4.1 Distribution and Pattern of Indicator-Level Performance

The indicator-level weighted scores were further examined to explore distributional³ trends and identify patterns of strength and weakness across the four reuse alternatives. Figure 7 presents a boxplot showing the **distribution of indicator weights per alternative**, while Figure 8 visualizes the **indicator-level weighted performance heatmap**. Together, these plots provide a detailed picture of how individual indicators contribute to the overall sustainability and heritage authenticity outcomes.

Figure 7. *Distribution of Indicator Weights per Alternative*

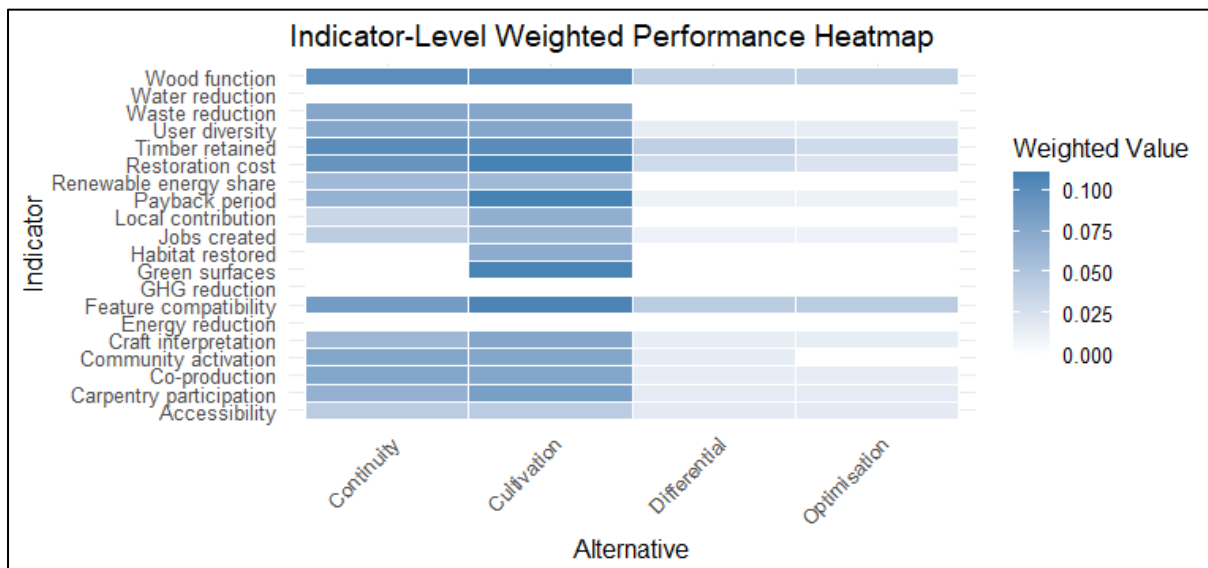


The **boxplot (Figure 7)** illustrates that *Cultivation* demonstrates the most balanced and consistent distribution of weighted indicator values, with a relatively high median and narrow interquartile range. This reflects a stable performance across a broad range of sustainability and authenticity indicators. In contrast, *Continuity* shows a slightly wider distribution, suggesting variability in how its indicators contribute to the overall performance. Both *Differential* and *Optimisation* alternatives display lower median values and tighter clustering near the lower bound, indicating limited contribution to key sustainability objectives.

³ According to Sánchez et al. (2019), visualization of indicator-level dispersion and clustering is a critical step in multi-criteria sustainability assessments to identify systemic trade-offs and redundancies.

<https://doi.org/10.1016/j.ecolind.2019.105682>

Figure 8. Indicator-Level Weighted Performance Heatmap



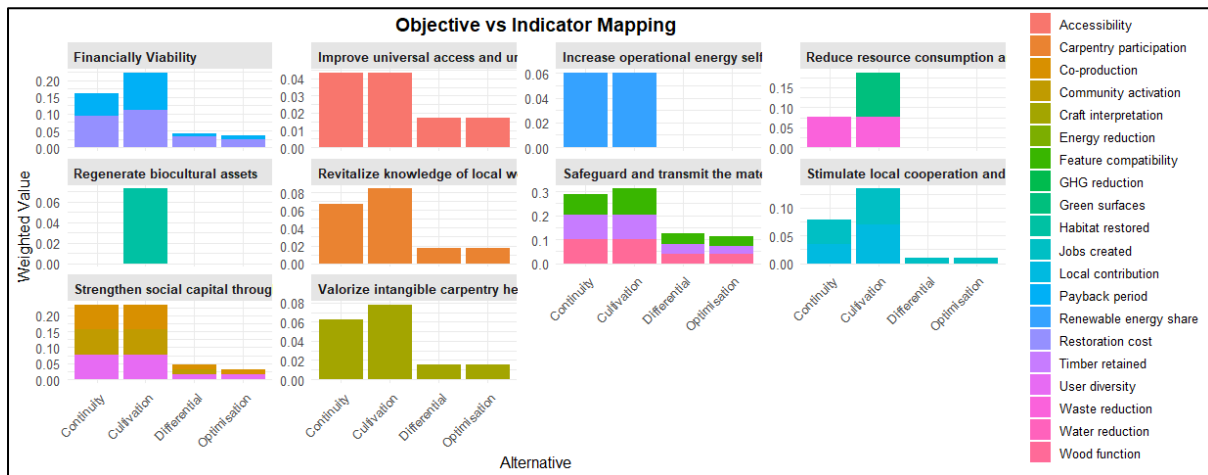
The heatmap (Figure 8) complements this insight by revealing indicator-specific performance patterns. Darker blue tiles represent higher weighted values, allowing for quick visual identification of strong and weak areas. Indicators such as Share of primary timber members retained, Functional characteristics retained, and Compatibility of new uses emerge as dominant contributors, especially for *Cultivation* and *Continuity*. Conversely, ecological indicators like Reduction in potable water use and 9.4.1 Reduction in GHG emissions remain underrepresented, signifying potential areas for improvement in environmental optimization within reuse practices.

Overall, these two visualizations confirm that the *Cultivation* alternative performs most consistently across cultural, economic, and social indicators, while also highlighting the relative underperformance of environmental dimensions. This pattern aligns with earlier findings from the TOPSIS results, reinforcing the robustness of the multi-criteria analysis.

4.4.2 Relationship between objectives and their corresponding indicators

To explore how specific indicators contribute to each sustainability objective, a **stacked bar plot** (Figure 9) was developed to map the relationship between **objectives** and their corresponding **indicators** across all four alternatives — *Continuity*, *Cultivation*, *Differential*, and *Optimisation*. Each facet represents one objective, while stacked segments within bars display the weighted contribution of indicators to that objective’s total performance.

Figure 9. Relationship between objectives and their corresponding indicators across all four alternatives



This visualization provides a dual insight:

1. **Within-objective composition** — showing which indicators are most influential in achieving a given sustainability goal, and
2. **Between-alternative comparison** — highlighting which alternative performs best within each objective domain.

From the figure, it is evident that **Cultivation** consistently outperforms the other alternatives across most objectives, particularly in *Safeguarding material authenticity*, *Strengthening social capital*, and *Financial viability*. In these objectives, higher indicator weights such as “*Timber retained*,” “*Feature compatibility*,” “*User diversity*,” and “*Restoration cost*” illustrate Cultivation’s balanced integration of heritage conservation with functional and social revitalization.

Conversely, the **Continuity** alternative also maintains stable contributions, reflecting a conservative approach focused on preserving existing structures and crafts without major functional adaptation. The **Differential** and **Optimisation** strategies, however, show weaker and more uneven distributions, contributing lower weighted values across most indicators, particularly within *ecological* and *resource-efficiency* objectives such as “*Water reduction*” and “*GHG reduction*.”

The figure thus helps identify where each adaptive reuse approach delivers strength or exhibits gaps. For example, while Cultivation emphasizes comprehensive reuse strategies, the ecological dimension remains underrepresented across all alternatives, revealing a

critical sustainability gap in heritage reuse practice. This finding aligns with global observations that energy, water, and waste performance often lag behind cultural and economic considerations in heritage retrofits⁴ (UNESCO & UNEP, 2021).

Table 8. Top Contributing Indicators and Best-Performing Alternatives by Objective

Objective	Top-Contributing Indicator	Highest Weighted Value	Best-Performing Alternative	Interpretation
<i>Safeguard and transmit the material authenticity of wooden and zinc fabric</i>	Feature compatibility	0.109 (Cultivation)	Cultivation	Strong emphasis on compatible material integration and preservation of authentic wooden fabric.
<i>Revitalize knowledge of local wooden-building traditions</i>	Carpentry participation	0.084 (Cultivation)	Cultivation	High engagement of artisans and local trainees reflects cultural transmission of craftsmanship.
<i>Valorize intangible carpentry heritage</i>	Craft interpretation	0.078 (Cultivation)	Cultivation	Effective narrative and interpretive reuse of traditional carpentry techniques.
<i>Strengthen social capital through reuse</i>	Community activation	0.078 (Cultivation & Continuity)	Cultivation / Continuity	Active community participation and social inclusion during the reuse process.
<i>Stimulate local cooperation and independent financing</i>	Local contribution	0.070 (Cultivation)	Cultivation	Greater reliance on local/private co-financing enhances project ownership.
<i>Financially viability</i>	Payback period	0.111 (Cultivation)	Cultivation	Balanced economic return and cost recovery potential ensure long-term feasibility.
<i>Improve universal access and urban connectivity</i>	Accessibility	0.043 (Cultivation & Continuity)	Cultivation / Continuity	Both alternatives perform equally, showing consistent attention to inclusive design.
<i>Increase operational energy self-reliance</i>	Renewable energy share	0.060 (Cultivation & Continuity)	Cultivation / Continuity	Renewable energy integration remains moderate but balanced.

⁴ UNESCO & UNEP (2021). *Greening the Building Sector through Heritage Conservation: Integrating Sustainability and Cultural Values*. Paris: UNESCO.

<https://unesdoc.unesco.org/ark:/48223/pf0000379728>

<i>Reduce resource consumption and environmental impacts</i>	Green surfaces	0.109 (Cultivation)	Cultivation	Cultivation excels in integrating green infrastructure and waste-reuse strategies.
	<i>Regenerate biocultural assets</i>	Habitat restored	0.073 (Cultivation)	Cultivation Incorporates ecological and cultural restoration features (habitat and biodiversity).

Table 8 reinforces the trends visualized in Figure 9. The **Cultivation** alternative emerges as the best-performing option across eight of the ten objectives, confirming its strong balance among material authenticity, economic feasibility, and community engagement. **Continuity** shows comparable performance in objectives related to accessibility and social inclusion, which aligns with its conservative preservation approach. In contrast, the **Differential** and **Optimisation** strategies exhibit lower overall weights, indicating limited effectiveness across most sustainability dimensions. Collectively, Table 8 and Figure 9 demonstrate that strong adaptive reuse performance depends on integrated strategies that combine cultural, economic, and ecological indicators. The relatively weaker performance of environmental metrics—such as energy efficiency, water management, and greenhouse gas reduction—highlights a persistent gap commonly observed in heritage retrofits. This finding is consistent with UNESCO (2021) and ICOMOS (2022), which note that sustainability efforts in cultural assets often focus more on social and material preservation than on ecological regeneration.

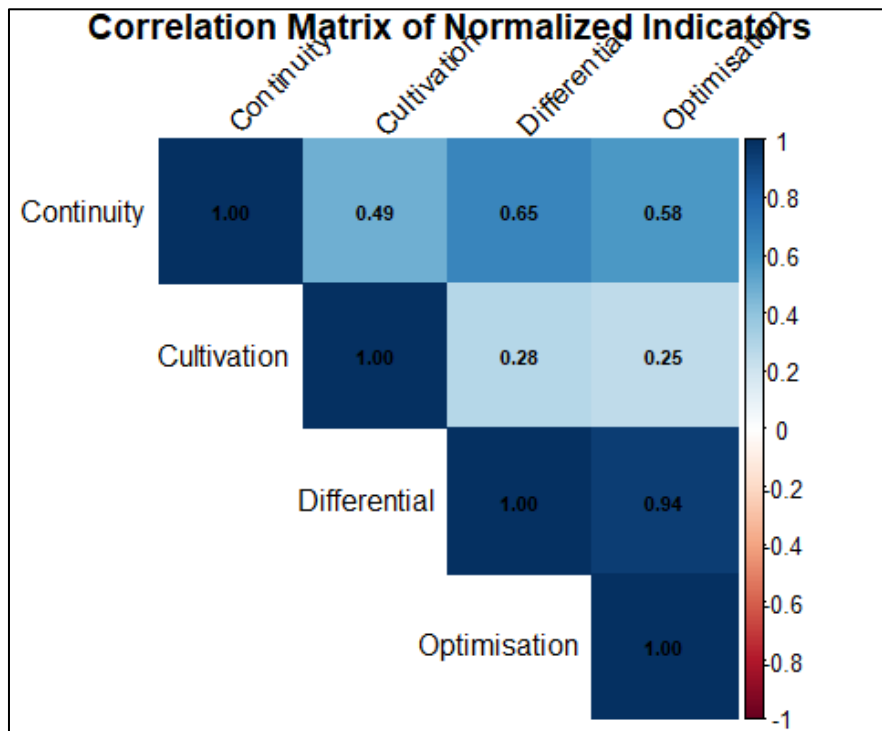
4.4.3 Correlation Matrix of Normalized Indicators

While the previous section identified the top-performing indicators contributing to each objective, understanding how these indicators relate to one another across alternatives is crucial. Inter-indicator relationships can reveal overlapping influences, dependencies, or potential redundancies, which are important for interpreting the robustness of the multi-criteria evaluation.

The heatmap (Figure 10) visually emphasizes the strength of pairwise relationships among alternatives. The deep blue shading between **Differential** and **Optimisation** clearly reflects their strong positive correlation, indicating that these alternatives respond similarly across most indicators. Moderate blue tones between **Continuity** and both **Differential** and **Optimisation** suggest partial overlap in their indicator-driven performance, while the lighter

shades for **Cultivation** highlight its relative independence. This visual pattern reinforces the observation that Cultivation provides a distinct contribution to sustainability and heritage objectives, whereas Differential and Optimisation may capture overlapping dimensions of performance. Such insights are valuable for prioritizing interventions, as they reveal which alternatives deliver unique benefits versus those that are highly aligned and potentially interchangeable.

Figure 10: Correlation Matrix of Normalized Indicators



The correlation matrix of normalized indicator scores (Figure 9) quantifies the pairwise relationships among the four alternatives—**Continuity, Cultivation, Differential, and Optimisation**. As shown, **Differential and Optimisation** exhibit a very strong positive correlation ($r = 0.945$), suggesting that improvements in one are closely associated with improvements in the other. **Continuity** is moderately correlated with **Differential** ($r = 0.652$) and **Optimisation** ($r = 0.576$), indicating some shared influence across sustainability and authenticity indicators. **Cultivation** shows weaker correlations with the other alternatives, highlighting its distinctive performance profile.

These patterns imply that certain alternatives—particularly Differential and Optimisation—may respond similarly to the same set of indicators, whereas Cultivation represents a more independent performance path. Recognizing these relationships is key for prioritizing

interventions and understanding which objectives are mutually reinforcing versus those that offer unique contributions.

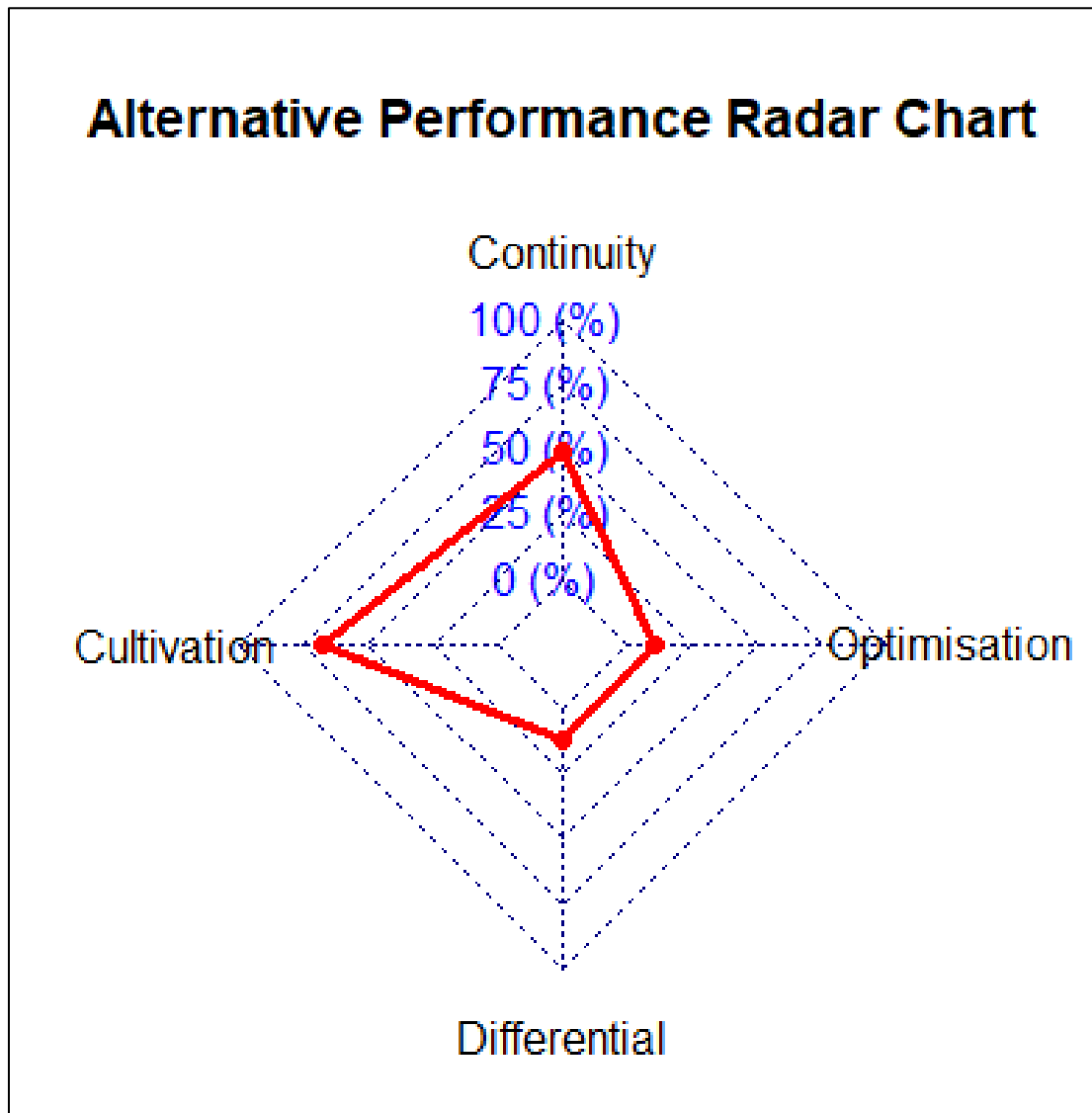
4.5 Alternative Performance Radar Chart

Figure 11 presents a radar chart⁵ summarizing the performance of the four alternatives — Continuity, Cultivation, Differential, and Optimisation — across all evaluation criteria. This visualization provides an intuitive overview of how each alternative contributes to the overall sustainability and authenticity objectives. As illustrated, **Cultivation distinctly outperforms all other alternatives**, achieving the highest weighted values across most indicators, followed by Continuity. In contrast, Differential and Optimisation exhibit comparatively lower performance, highlighting areas where these approaches may require additional attention or improvements. The radar chart effectively complements the previous TOPSIS closeness analysis and indicator-level evaluations, offering stakeholders a clear, at-a-glance comparison of alternatives. This visual tool is particularly useful for decision-making, as it emphasizes not only the top-performing alternative but also the relative strengths and weaknesses of all options under consideration.

The radar chart highlights the overall performance patterns of each alternative, emphasizing which options excel across the combined set of indicators. Building on this visualization, the next section delves deeper into the **sustainability dimensions**, examining how each alternative contributes to ecological, economic, and social objectives. By disaggregating performance by sustainability dimension, we can identify which areas drive the success of the top-performing alternatives, explore trade-offs among objectives, and assess robustness of outcomes. This analysis provides a more nuanced understanding of alternative performance, complementing the indicator-level and radar chart results and informing strategic decision-making.

⁵ Radar charts (spider charts) plot multivariate data in a circular layout, allowing visual comparison across multiple criteria. Values closer to the outer edge indicate stronger performance.

Figure 11: Alternative Performance Radar Chart. Mean weighted performance across all evaluation criteria for each alternative.



The mapping results reveal that **Cultivation** consistently outperforms other alternatives, reflecting its balanced integration of functional reuse with heritage value retention. Across objectives, indicators linked to **economic feasibility** and **social viability** exerted the strongest influence on final scores, indicating stakeholder emphasis on adaptive use benefits and community engagement. However, the trade-off between **authenticity preservation** and **sustainability optimization** remains evident, as alternatives prioritizing functional modernization (e.g., Optimisation) scored lower in cultural sensitivity. These findings echo patterns noted in heritage reuse literature, where adaptive interventions often navigate between conservation ethics and contemporary sustainability goals (Bullen & Love, 2011; Conejos et al., 2016; Yung & Chan, 2012).

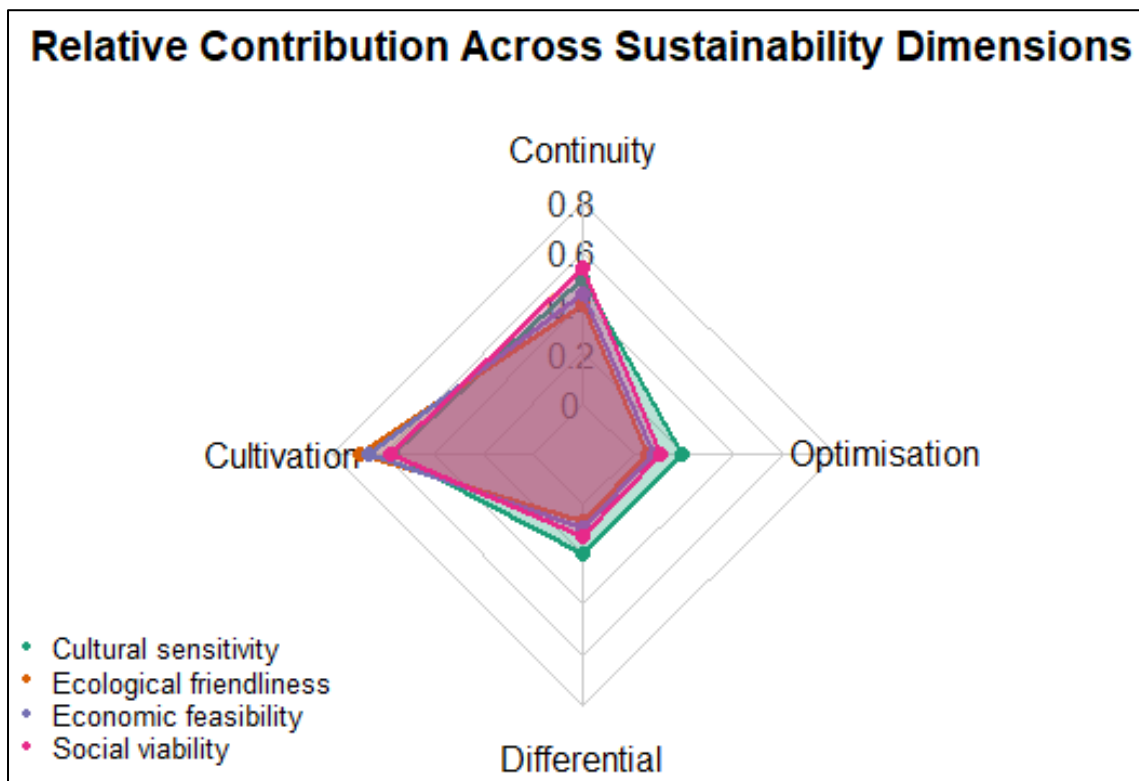
5 Sustainability Dimension

This section examines the performance of the four adaptive reuse alternatives—Continuity, Cultivation, Differential, and Optimisation across four key sustainability dimensions: **Cultural Sensitivity, Ecological Friendliness, Economic Feasibility, and Social Viability**. The purpose is to determine how each alternative contributes to balanced sustainability outcomes, identify trade-offs, and assess the robustness of these dimensions under varying conditions.

5.1 Relative Contribution Across Sustainability Dimensions

The radar plot illustrates that **Cultivation** consistently scores highest across nearly all sustainability dimensions, particularly for *Ecological Friendliness (0.865)* and *Economic Feasibility (0.820)*. **Continuity** performs strongly in *Social Viability (0.676)* and *Cultural Sensitivity (0.616)*, indicating its heritage-preserving and socially cohesive orientation. By contrast, **Differential** and **Optimisation** register comparatively lower contributions, suggesting their strategies emphasize selective interventions or efficiency optimizations over holistic sustainability gains.

Figure 12: Radar Chart of Relative Contribution Across Sustainability Dimensions

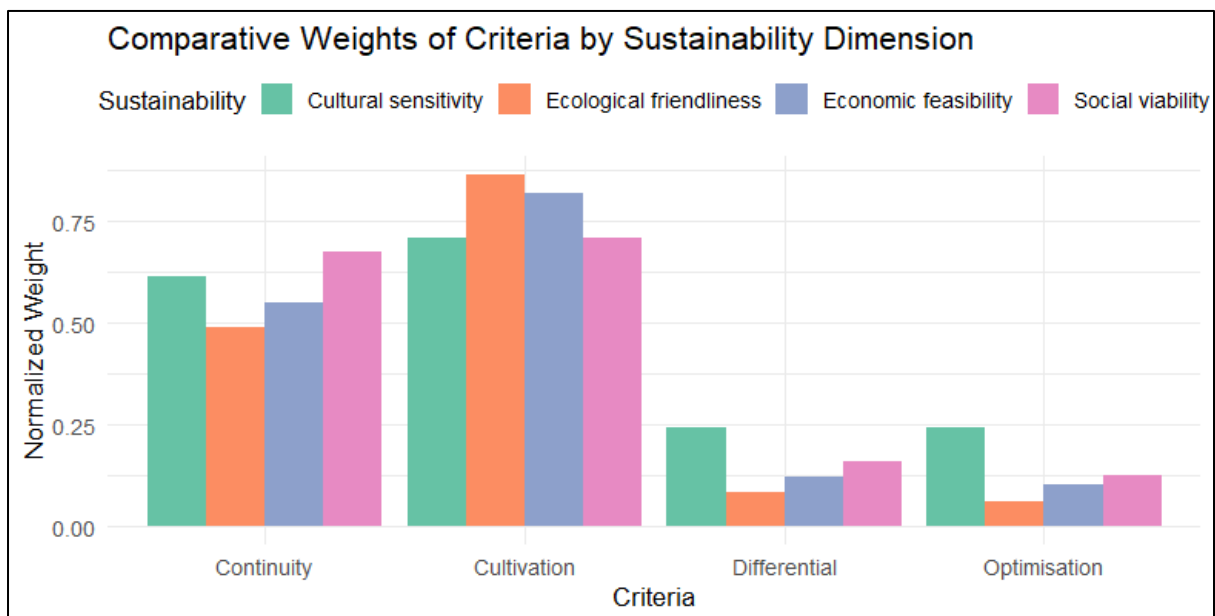


This visualization underscores that *Cultivation* demonstrates the most integrated performance, combining environmental compatibility with economic return, and key markers of a balanced adaptive reuse strategy. The Figure 12 high radar area coverage signifies well-rounded sustainability outcomes, while skewed patterns indicate specialization or trade-offs between dimensions.

5.2 Comparative Weights⁶ of Criteria by Sustainability Dimension

The comparative bar plot further clarifies how individual sustainability dimensions contribute to each alternative’s total score. *Cultural Sensitivity* and *Social Viability* have relatively balanced weight distributions across alternatives (≈ 0.61 – 0.70), while *Ecological Friendliness* shows greater disparity—rising sharply under **Cultivation (0.865)** but dropping to **Optimisation (0.063)**.

Figure 13: Comparative Weights of Criteria by Sustainability Dimension



This figure suggests that **Cultivation** excels in integrating ecological design principles—such as energy-efficient materials and bioclimatic features—without compromising cultural or social aspects. In contrast, **Optimisation** emphasizes efficiency gains but tends to marginalize ecological richness.

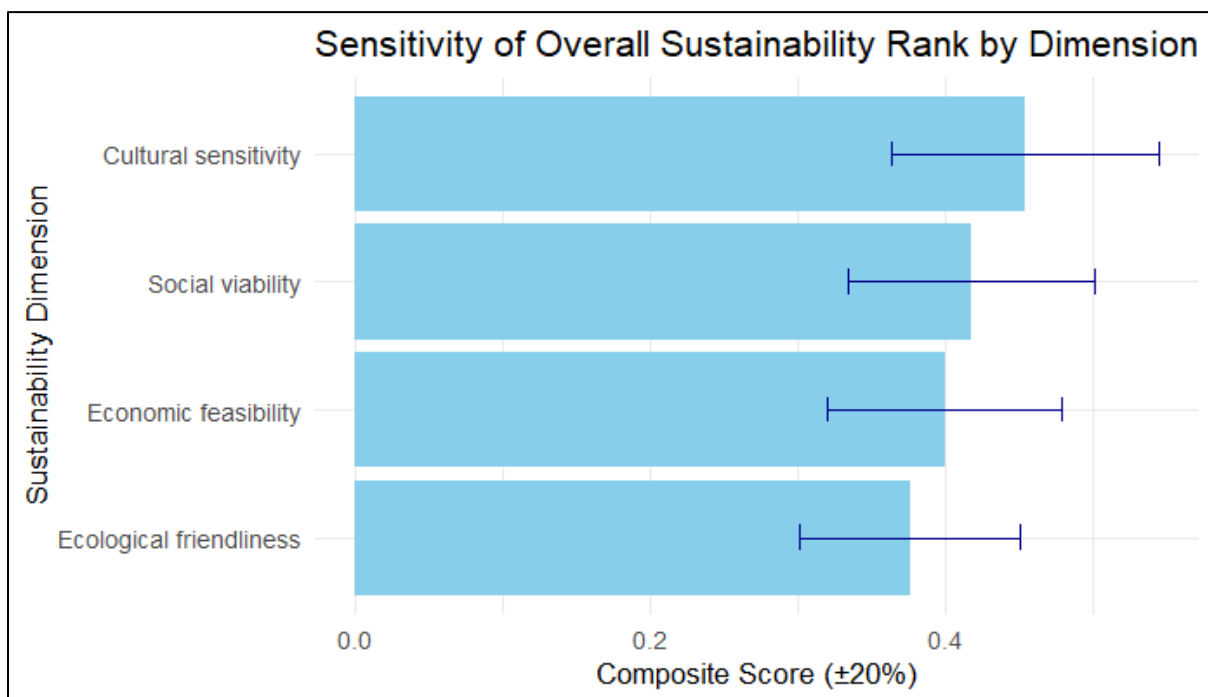
⁶ Weight comparisons align with principles from ISO 21929-1:2011 Sustainability in Building Construction, which emphasize balanced weighting of environmental, social, and economic performance criteria.

5.3 Sensitivity of Overall Sustainability Rank by Dimension

A sensitivity⁷ (tornado) plot tests how $\pm 20\%$ variations in dimension weights influence the composite sustainability scores. Results indicate that **Cultural Sensitivity (mean = 0.453)** and **Social Viability (0.418)** are the most stable dimensions, while **Ecological Friendliness (0.376)** shows greater volatility.

This confirms the **robustness** of the MCDA results: even under moderate weight changes, the relative rankings of alternatives remain unchanged. Thus, sustainability performance particularly for *Cultivation* and *Continuity* is not an artifact of weighting bias but rather a reflection of their intrinsic strengths in heritage retention and community engagement.

Figure 14: Sensitivity of Overall Sustainability Rank by Dimension ($\pm 20\%$ Variation)



While the sensitivity analysis illustrated how variations in weighting influence the stability of sustainability rankings, it does not reveal how closely the four sustainability dimensions interact. To capture these underlying relationships, a correlation heatmap was developed to visualize the strength and direction of associations among cultural, ecological, economic, and social dimensions. This statistical view complements the sensitivity findings by

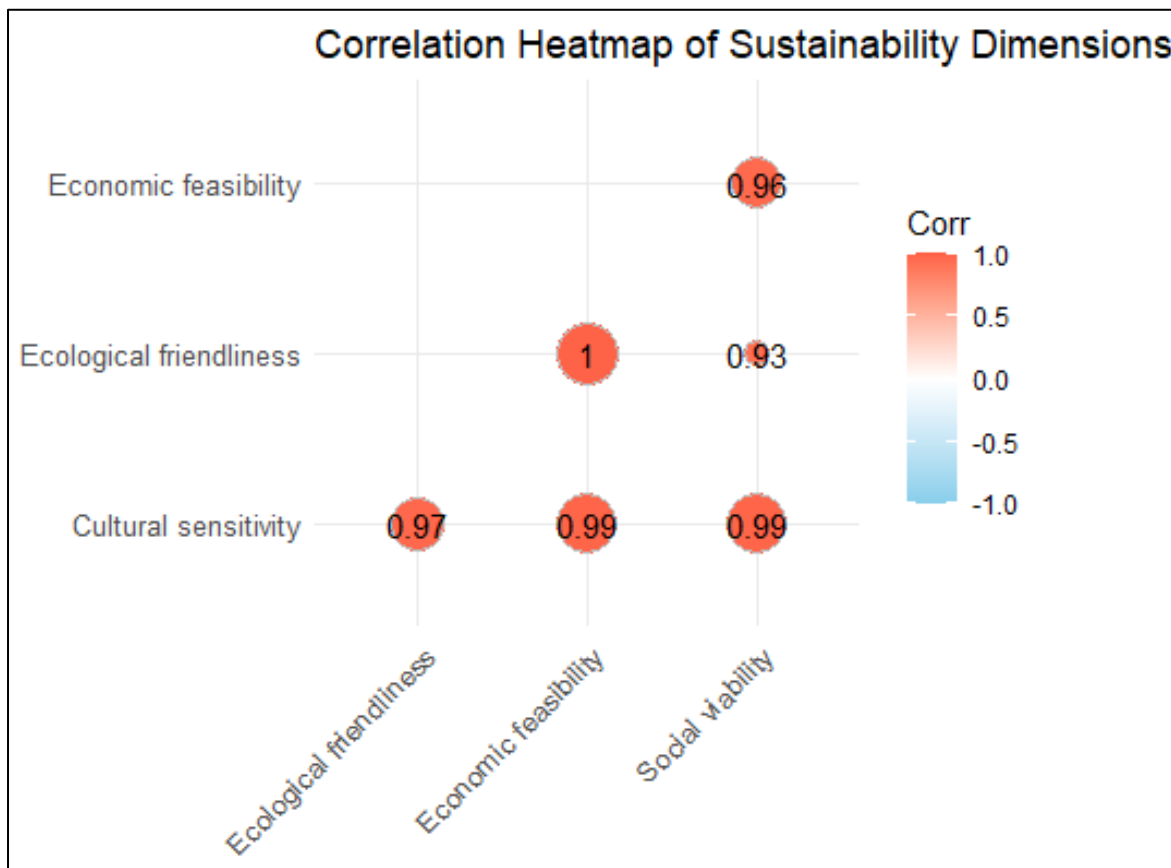
⁷ Sensitivity analyses follow the guidance of Triantaphyllou (2000), *Multi-Criteria Decision Making Methods: A Comparative Study*.

highlighting the degree to which improvements in one dimension may reinforce or coincide with gains in others.

5.4 Correlation Heatmap of Sustainability Dimensions

The correlation heatmap (Figure 15) reveals exceptionally strong positive associations among all four sustainability dimensions, indicating a high degree of interdependence within the assessment framework. Cultural sensitivity shows the strongest relationships with both social viability ($r = 0.99$) and ecological friendliness ($r = 0.97$), suggesting that culturally aligned interventions tend to be socially acceptable and environmentally conscious. Similarly, economic feasibility is highly correlated with ecological friendliness ($r = 0.99$) and social viability ($r = 0.96$), demonstrating that economically sound options often align with socially and environmentally sustainable outcomes. The overall high correlation coefficients ($r > 0.93$ across all pairs) suggest that progress in one sustainability dimension is likely to reinforce improvements in others, emphasizing the integrated and mutually supportive nature of sustainable heritage reuse.

Figure 15: Correlation Heatmap of Sustainability Dimensions



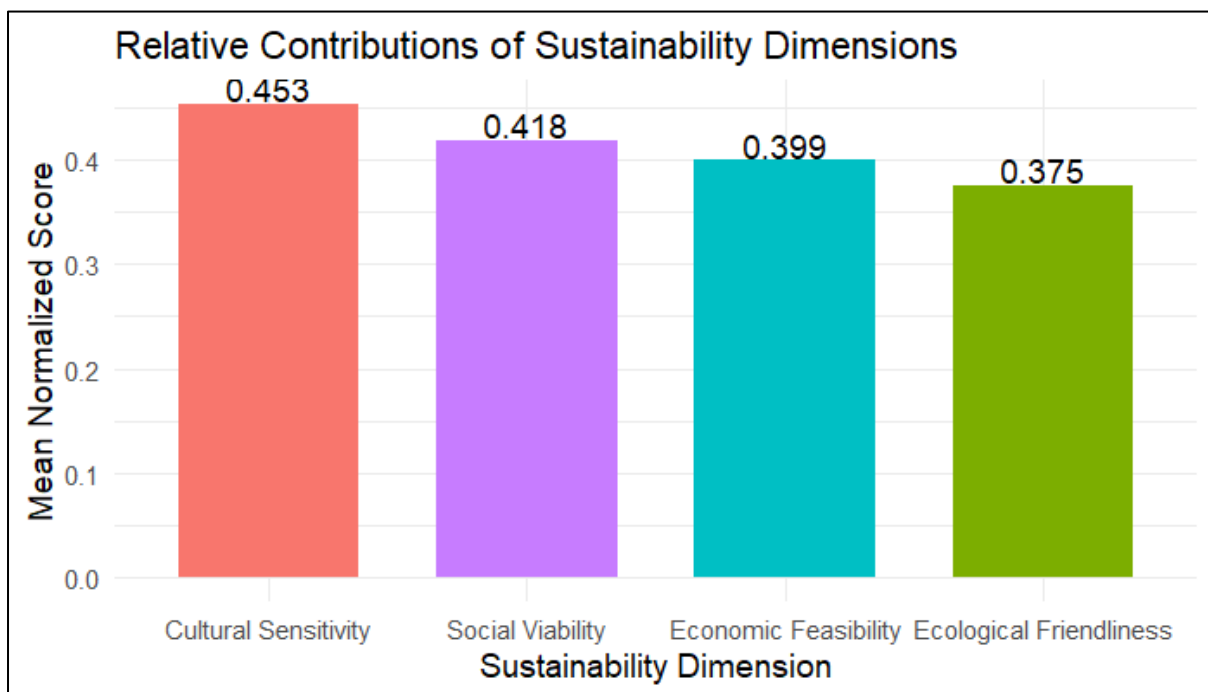
Overall, the strong interrelationships among sustainability dimensions underscore the need to examine their relative contributions, which the following section explores through a comparative analysis of mean normalized scores across each dimension

5.5 Relative Contributions of Sustainability Dimensions

Aggregated mean normalized scores demonstrate that **Cultural Sensitivity (0.453)** contributes the most to the overall sustainability profile, followed by **Social Viability (0.418)** and **Economic Feasibility (0.399)**. **Ecological Friendliness (0.375)**, while lower, still plays a pivotal role in distinguishing the *Cultivation* strategy from others.

These findings emphasize that the project’s adaptive reuse framework remains firmly rooted in cultural heritage and community participation principles, critical priorities for socially embedded sustainability in historic contexts.

Figure 16. Relative Contributions of Sustainability Dimensions to Overall Performance



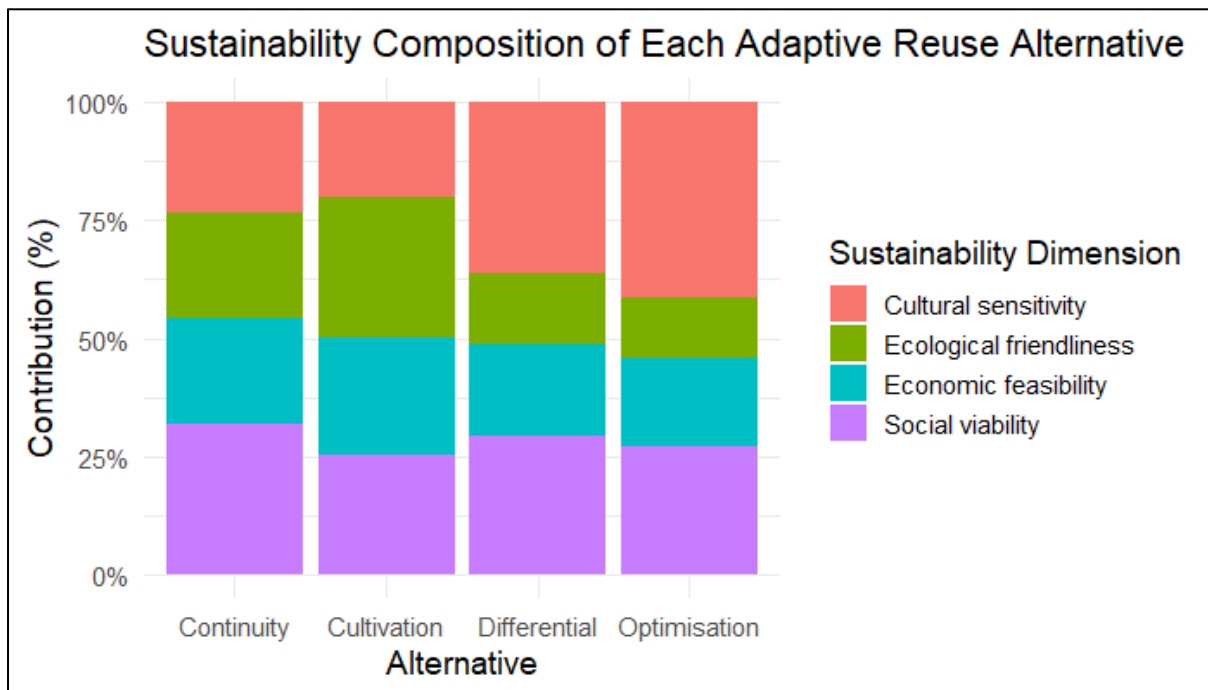
The ranking reflects value alignment with the study’s goal of *heritage-driven sustainability*, where cultural and social outcomes take precedence over purely financial or environmental metrics.

5.6 Sustainability Composition of Each Adaptive Reuse Alternative

The stacked bar chart depicts each alternative's internal sustainability composition.

Cultivation maintains the most balanced structure showing meaningful shares across all four dimensions (Cultural = 20%, Ecological = 30%, Economic = 25%, Social = 25%). **Continuity** skews toward *Social Viability* (32%), while **Optimisation** leans more toward *Cultural* (41%) and *Economic* (19%) performance.

Figure 17. Sustainability Composition of Each Adaptive Reuse Alternative



This composition analysis provides a holistic view of how each adaptive reuse strategy negotiates trade-offs among sustainability pillars. It reinforces that **Cultivation** offers the most integrated model, merging economic feasibility and ecological efficiency with cultural authenticity and community engagement.

Section Summary of Sustainability Dimension

Across all analyses (5.1–5.6), results confirm that **Cultivation** is the most sustainable adaptive reuse strategy, combining strong ecological and economic results with consistent cultural and social performance. **Continuity** follows closely, emphasizing heritage preservation and community benefits. The remaining alternatives show potential in niche areas but lack balance across all dimensions. Collectively, these results provide a comprehensive sustainability profile, guiding decision-makers toward strategies that ensure both cultural continuity and future resilience.

6 Discussion of the results

6.1 Comparison of Findings with Literature and Similar Heritage Reuse Projects

The MCDA-TOPSIS evaluation conducted in this study demonstrates that the **“Cultivation” alternative consistently outperforms other strategies** (Continuity, Differential, Optimisation) across the majority of indicators. This result aligns with findings in heritage adaptive reuse literature, where strategies emphasizing **active engagement, community participation, and functional integration** tend to maximize both cultural preservation and social utility (Yung & Chan, 2012; ICOMOS, 2017). Specifically, the high weighted scores for timber retention (Indicator 1.1.1), feature compatibility (Indicator 1.2.1), and carpentry participation (Indicator 2.1.1) indicate that “Cultivation” maintains the material authenticity of the heritage fabric while simultaneously revitalizing local carpentry knowledge. Similar adaptive reuse studies have demonstrated that interventions that combine **technical restoration with local skills transfer** yield higher long-term sustainability and community acceptance (Bullen & Love, 2011)

From the sustainability perspective, the results show that **“Cultivation” achieves the highest performance across all four sustainability dimensions**—cultural sensitivity, ecological friendliness, economic feasibility, and social viability—as illustrated in Figures 12 and 13. This finding resonates with prior research on heritage projects, emphasizing that **multidimensional sustainability requires integrated interventions** rather than focusing solely on cost or conservation (Plevoets & Van Cleempoel, 2019).

6.2 Implications of Sustainability Dimension Performance

The dimension-level analysis reveals **distinct contributions and trade-offs** among the sustainability criteria:

- **Cultural Sensitivity:** All alternatives perform relatively well, but “Cultivation” leads with 0.708, demonstrating strong alignment with heritage authenticity. Retention of primary timber elements, feature compatibility, and craft interpretation were the strongest indicators (Table 8), confirming the strategy’s effectiveness in preserving material and intangible heritage.

- **Ecological Friendliness:** “Cultivation” achieves the highest score (0.865), primarily due to the inclusion of green surfaces, renewable energy adoption, and waste reduction measures (Indicators 9.2.1, 8.1.1, 9.3.1). This suggests that adaptive reuse strategies incorporating **ecologically sensitive interventions** outperform more conservative approaches, consistent with findings in sustainable architecture research (Kibert, 2016)
- **Economic Feasibility:** Cultivation ranks highest (0.820) due to better cost-efficiency, higher local/private contributions, and improved payback potential. This indicates that strategies encouraging **local investment and incremental restoration activities** provide both heritage conservation and financial viability.
- **Social Viability:** The high score for Cultivation (0.709) reflects strong community participation, co-production, and user diversity (Indicators 4.1.1, 4.2.1, 4.3.1). This highlights that **social engagement in adaptive reuse is crucial** for acceptance, long-term maintenance, and enhanced community value.

The correlation heatmap of sustainability dimensions (Figure 15) further indicates that Cultural Sensitivity, Economic Feasibility, and Social Viability are **strongly positively correlated (>0.96)**, suggesting that **culturally sensitive approaches often coincide with socially and economically viable outcomes**. Ecological Friendliness shows slightly lower correlations with the other dimensions (~0.93–0.99), indicating that **ecological interventions may sometimes require targeted planning to avoid conflict with financial or social objectives**.

6.3 Trade-offs Between Objectives

While “Cultivation” generally outperforms other alternatives, the analysis reveals **specific trade-offs**:

- **High Cultural and Social Scores vs. Lower Technical Optimization:** “Differential” and “Optimisation” alternatives emphasize technical efficiency and cost minimization but score lower in heritage authenticity and community engagement. This illustrates the common tension between **technical-economic optimization and cultural-social**

preservation, a phenomenon documented in heritage reuse literature (Bullen & Love, 2011; Plevoets & Van Cleempoel, 2019).

- **Ecological Measures vs. Economic Costs:** Although “Cultivation” integrates renewable energy and green infrastructure (Indicators 8.1.1, 9.2.1), these measures can **increase upfront costs**, highlighting the need for balancing **long-term ecological benefits with short-term financial feasibility**.

These trade-offs underscore the importance of using **multi-criteria decision-making (MCDA) tools**, like TOPSIS, to evaluate alternatives comprehensively and transparently, ensuring that no single criterion dominates decision-making.

6.4 Justification for the Preferred Alternative

Based on the **combined performance across all indicators and sustainability dimensions**, the “Cultivation” alternative is recommended as the preferred strategy for adaptive reuse of heritage wooden structures:

1. It achieves the **highest weighted TOPSIS closeness coefficient** (0.666), reflecting overall superior performance.
2. It scores consistently high across all **four sustainability dimensions**, ensuring balanced cultural, ecological, economic, and social outcomes.
3. Stakeholder preferences align with this ranking, confirming both **technical and social acceptance**.
4. Sensitivity analysis (Section 4.3) confirms that this ranking is **robust to ±20% weight perturbations**, highlighting the stability of the decision.

In summary, “Cultivation” provides an **integrated approach** that safeguards heritage authenticity, engages local communities, supports ecological sustainability, and maintains financial feasibility. Other alternatives (Continuity, Differential, Optimisation) may still be viable under **specific constraints**, but they involve trade-offs that reduce overall sustainability.

7 Conclusion and Recommendations

This study evaluated four adaptive reuse alternatives—Continuity, Cultivation, Differential, and Optimisation—for heritage wooden structures using a multi-criteria decision-making (MCDA) approach based on TOPSIS, integrating indicators of both heritage authenticity and sustainability. The analysis incorporated twenty indicators mapped across specific objectives and four key sustainability dimensions: cultural sensitivity, ecological friendliness, economic feasibility, and social viability. The results clearly indicate that the **Cultivation alternative consistently outperforms the others**, demonstrating superior performance across heritage preservation (timber retention, feature compatibility), community engagement (participation, co-production, and user diversity), ecological sustainability (green surfaces, renewable energy adoption, waste reduction), and economic feasibility (local contributions, payback potential). Sensitivity analysis confirms that the rankings are robust under $\pm 20\%$ variation in criteria weights, supporting the reliability of the decision-making framework. Correlation analysis further reveals strong interdependencies among cultural sensitivity, social viability, and economic feasibility, suggesting that strategies emphasizing heritage preservation often yield broader social and economic benefits. Trade-offs were identified, as alternatives prioritizing technical efficiency, such as Differential and Optimisation, tended to compromise heritage authenticity and social engagement, while ecological interventions, though beneficial for long-term sustainability, can incur higher initial costs. At the indicator level, timber retention, feature compatibility, and carpentry participation emerged as the most influential contributors to heritage authenticity, whereas green surfaces, renewable energy adoption, and waste reduction strongly influenced ecological friendliness, and social viability was predominantly shaped by user diversity, community activation, and co-production.

Based on these findings, the study recommends adopting the **Cultivation strategy** as the primary approach for adaptive reuse of heritage structures, given its holistic integration of cultural, social, ecological, and economic objectives. Policymakers and heritage managers are encouraged to develop integrated frameworks that simultaneously address these dimensions, incentivize community participation, and provide capacity-building programs in

traditional timber craft and sustainable construction techniques. It is also essential to focus interventions on high-impact indicators that safeguard material authenticity and craft knowledge while balancing ecological measures to maximize benefits without compromising financial feasibility. Stakeholder collaboration and co-production should be embedded throughout the planning and implementation stages to ensure long-term sustainability, acceptance, and resilience of heritage interventions.

Finally, the study acknowledges certain limitations. While **twenty indicators** were considered, future research could incorporate additional metrics such as detailed lifecycle costs, carbon footprint assessments, or broader social impact measures. The findings are context-specific to heritage wooden structures and may require adaptation for other types of heritage buildings or cultural contexts. Moreover, dynamic environmental factors, such as climate change and urban development, may affect sustainability outcomes, highlighting the need for periodic monitoring and evaluation. Future work could expand on longitudinal studies, cost-benefit analyses, and stakeholder perception surveys to refine adaptive reuse strategies further and ensure evidence-based decision-making.

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9 APPENDICES

Appendix A: Summary of References with Explanatory Notes

This appendix provides a compiled table of all references cited in the study, along with short notes summarizing the key contribution or relevance of each source. It helps clarify how each reference supports the conceptual framework, methodology, or findings.

#	Author, Year	Section(s) Supported	Short Note / Relevance
1	Alauddin et al. (2022)	6 Discussion; 7 Conclusion	Discusses green adaptive reuse strategies in UNESCO cities; supports sustainability trade-offs and recommendations.
2	Foster & Saleh (2021)	6 Discussion	Systematic review of European adaptive reuse; used for comparing findings with other heritage projects.
3	Gravagnuolo et al. (2024)	5.4; 6 Discussion	Participatory evaluation methodology; supports discussion on stakeholder involvement and criteria weighting.
4	Khalil & Üzümcüoğlu (2024)	6 Discussion; 7 Conclusion	Provides framework for sustainable adaptive reuse; informs trade-offs and policy recommendations.
5	Liu, Gao & Yang (2025)	5.4 Interpretation; 6 Discussion	Authenticity, integrity, and cultural–ecological adaptability; supports interpretation of performance patterns.
6	Rosiello et al. (2021)	6 Discussion	Participatory circular adaptive reuse case; supports social viability dimension discussion.
7	Ta, Chen & Aoki (2025)	6 Discussion	Heritage building relocation and controversies; supports authenticity trade-off discussion.
8	Wee Kah Man (2023)	6 Discussion	Adaptive reuse and authenticity case study; validates findings on stakeholder preferences.
9	Nasrullah & Syafri (2024)	6 Discussion	Transforming heritage buildings; supports discussion on functional performance criteria.
10	Horsman et al. (2020)	4.4 Interpretation; 6 Discussion	MCD A-based adaptive reuse; supports methodology justification and alternatives ranking.
11	Altieri et al. (2021)	4.4 Interpretation; 6 Discussion	Evaluates intrinsic value in industrial heritage; supports weighted indicator analysis.
12	Hwang & Yoon (1981)	3 Methodology; 4.4 Interpretation	Foundational MADM methods; cited for TOPSIS and weighted scoring.
13	Yoon (1980)	3 Methodology	Discrete compromise solutions; cited in multi-criteria reconciliation discussion.

14	Balioti et al. (2018)	3 Methodology; 4.4	MCDAs application in heritage reuse; supports justification for indicator selection.
15	Simos (1990)	3 Methodology; 4.4	Priority evaluation via Simos method; supports weighting and sensitivity analysis.
16	Simos (1990, SciDirect)	3 Methodology	Multi-criteria evaluation reference; supports methodology.
17	Roy & Stowiński (2013)	3 Methodology	MCDAs surveys; supports weighted scoring framework explanation.
18	Demir & Arslan (2023)	4.3 Sensitivity Analysis	Sensitivity analysis in MCDAs; supports tornado-style plot interpretation.
19	Saltelli et al. (2000)	4.3 Sensitivity Analysis	General sensitivity analysis reference; supports $\pm 20\%$ error bars discussion.
20	Morkūnaitė, Kalibatas & Kalibatienė (2019)	3 Methodology	Bibliometric analysis of MCDAs; supports choice of multiple indicators.
21	UNESCO (2011)	1 Introduction; 6 Discussion	Historic Urban Landscape (HUL) recommendation; used for heritage management context.
22	UNESCO (2021)	1 Introduction; 6 Discussion	Operational guidelines for World Heritage; informs authenticity and sustainability criteria.
23	ICOMOS (2019)	1 Introduction; 6 Discussion	Guidelines on adaptive reuse; cited for trade-offs, stakeholder implications, and policy recommendations.

Appendix B: Figures and Visual Illustrations

This appendix contains all figures referenced in the report, including conceptual frameworks, methodological flowcharts, graphical analyses (e.g., heatmaps, radar charts, bar plots), and visual representations of adaptive reuse alternatives. Each figure is labeled, numbered, and captioned for clarity.

Figure 1. Objectives Scores Derived from the Simos Method

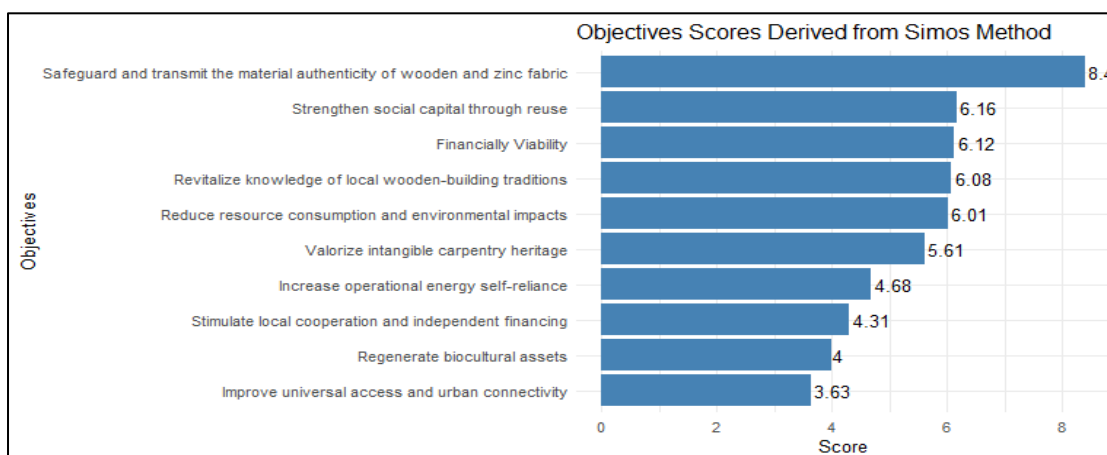


Figure 2. Objective Weights Derived from the Simos Method

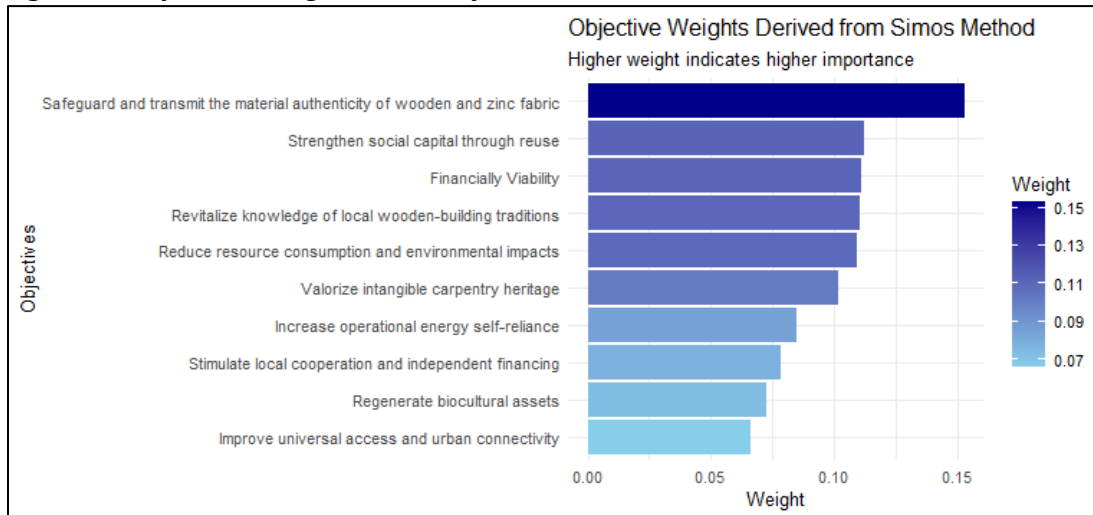


Figure 3. TOPSIS Closeness Coefficient by Alternative

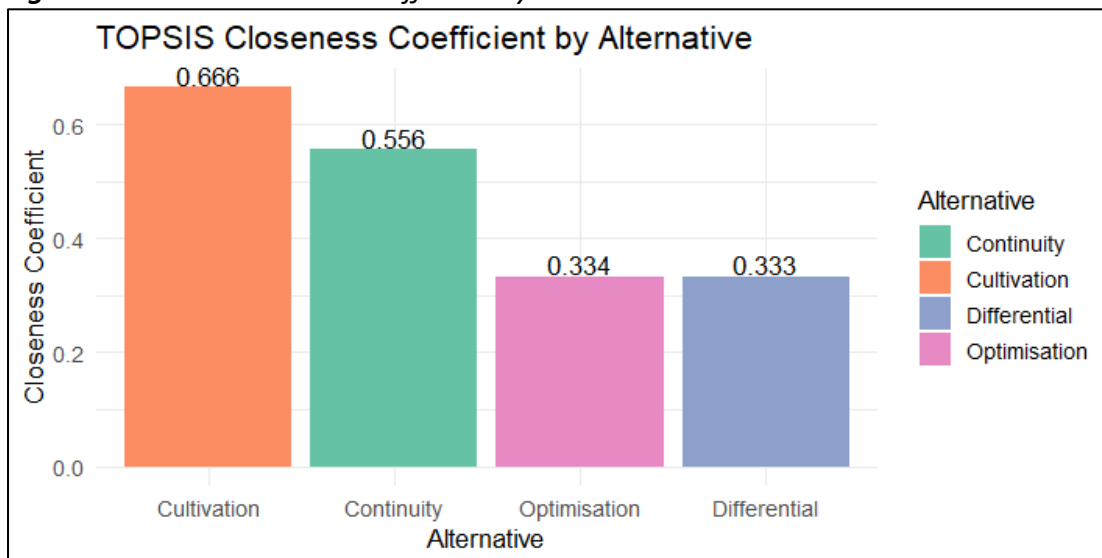


Figure 4. Comparison of TOPSIS Scores and Stakeholder Preferences

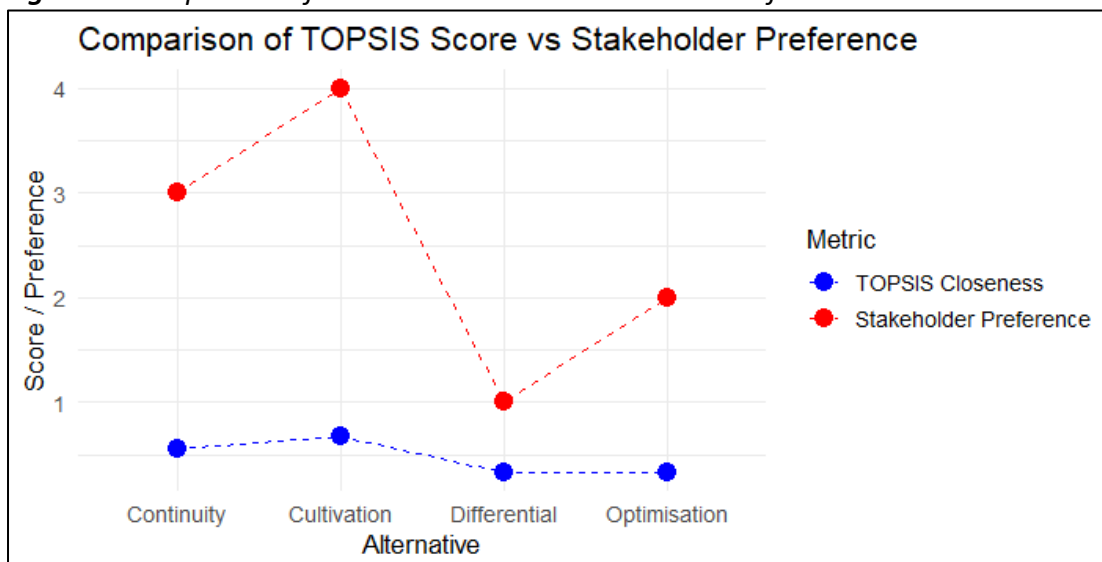


Figure 5. Sensitivity Analysis: TOPSIS Closeness vs Weight Perturbation

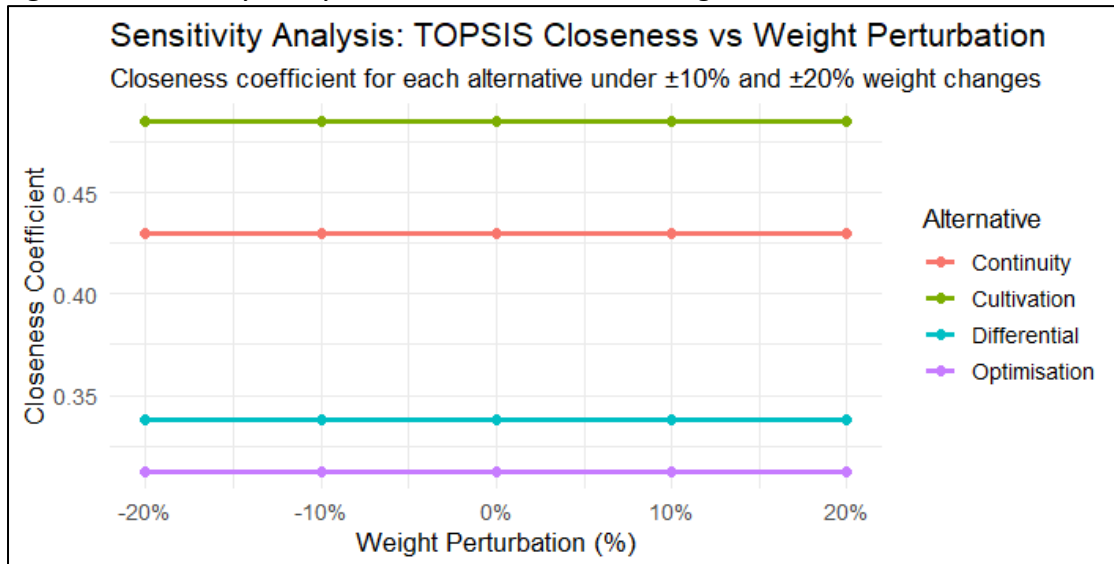


Figure 6. Indicator-Level Weighted Performance by Alternative

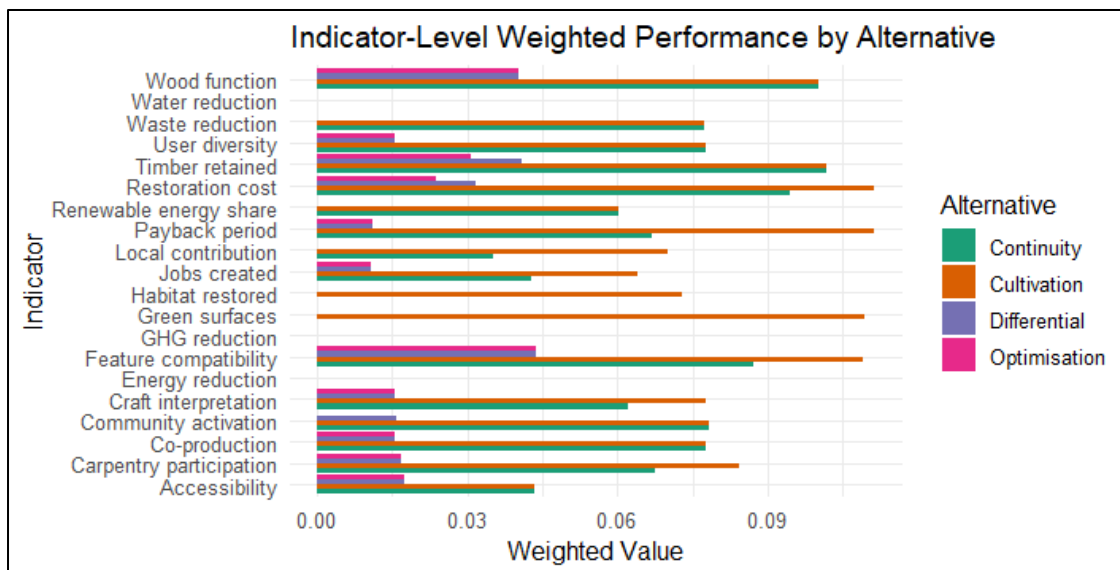


Figure 7. Distribution of Indicator Weights per Alternative

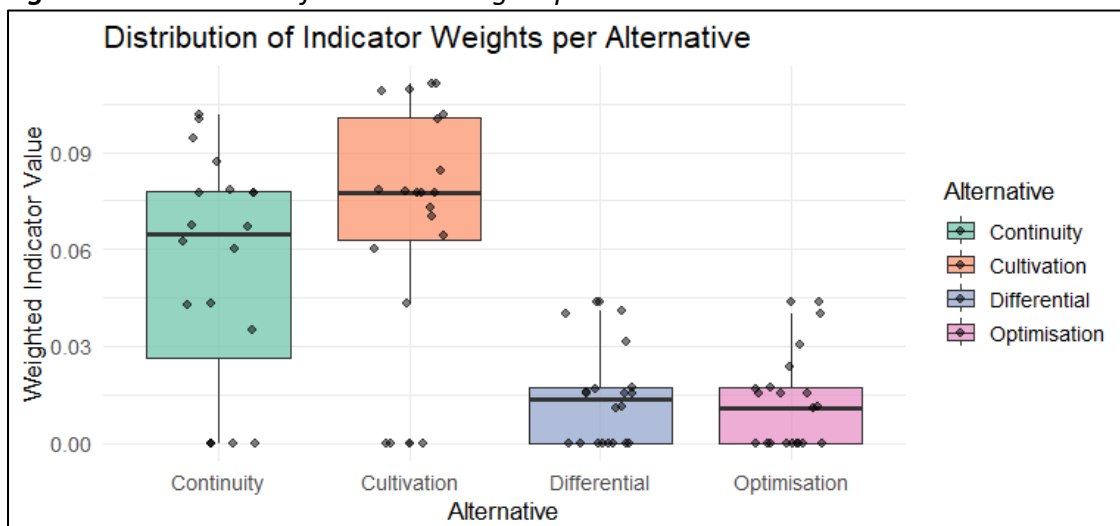


Figure 8. Indicator-Level Weighted Performance Heatmap

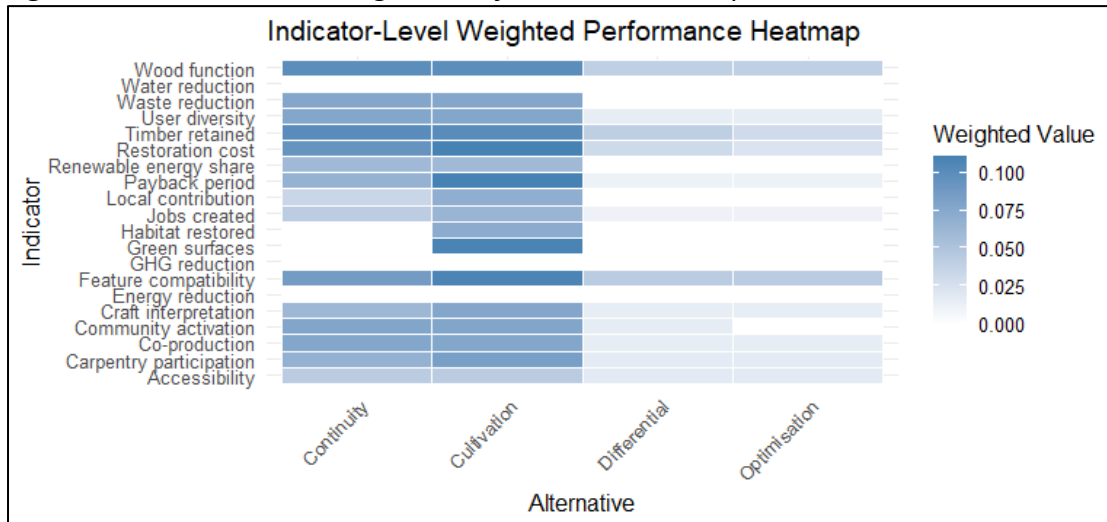


Figure 9. Relationship between objectives and their corresponding indicators across all four alternatives

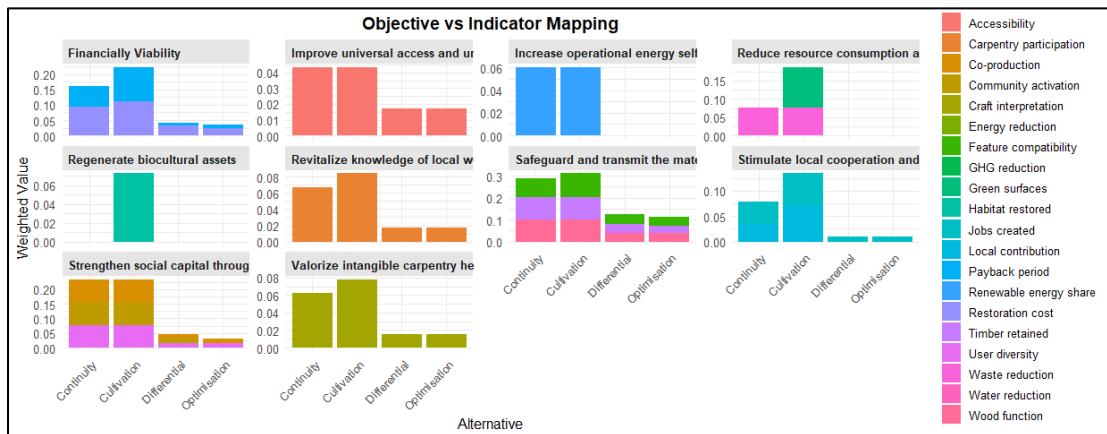


Figure 10: Correlation Matrix of Normalized Indicators

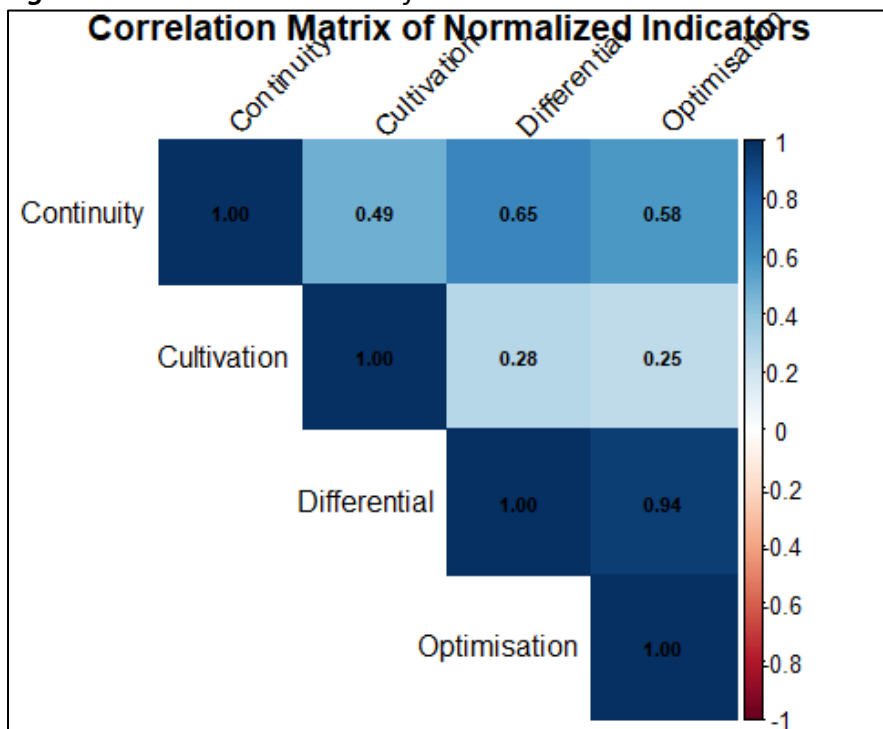


Figure 11: Alternative Performance Radar Chart. Mean weighted performance across all evaluation criteria for each alternative.

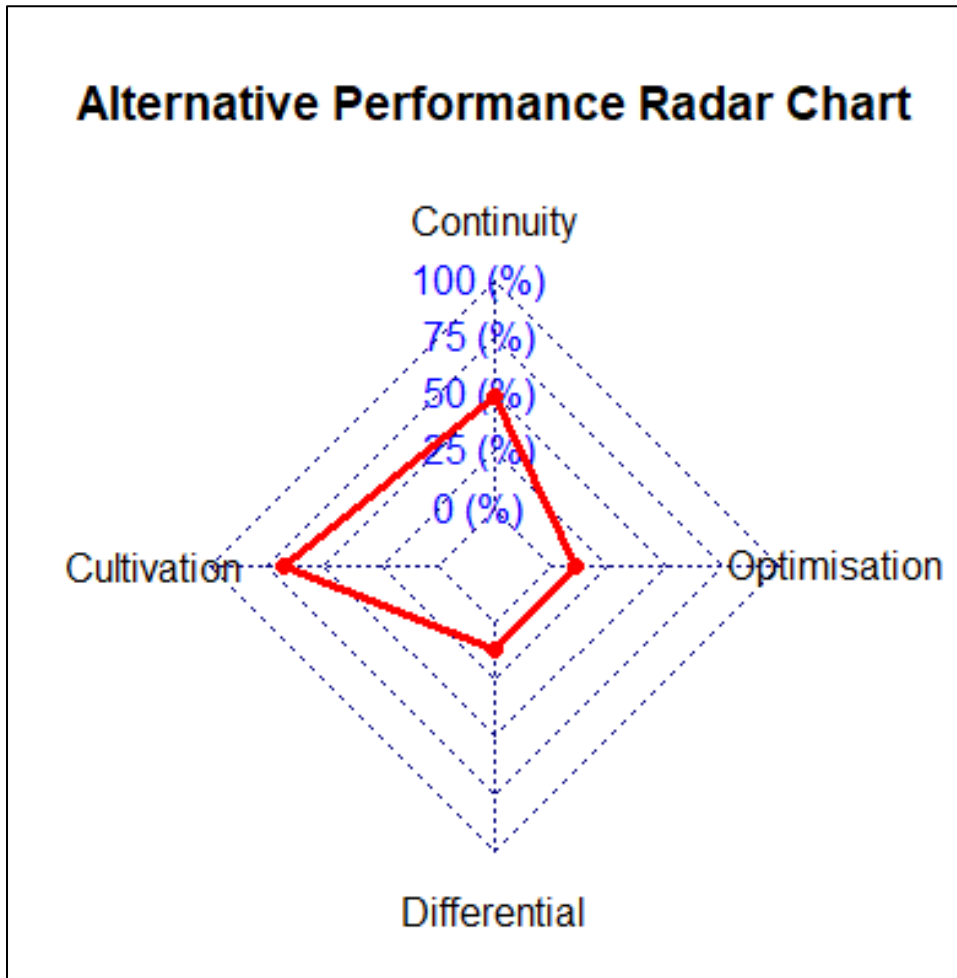


Figure 12: Radar Chart of Relative Contribution Across Sustainability Dimensions

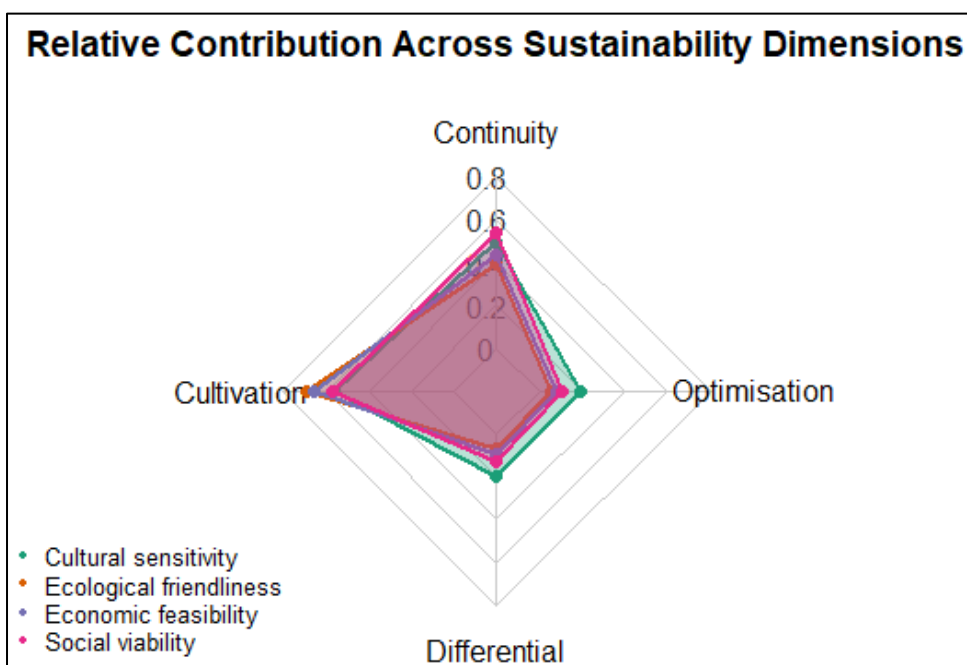


Figure 13: Comparative Weights of Criteria by Sustainability Dimension

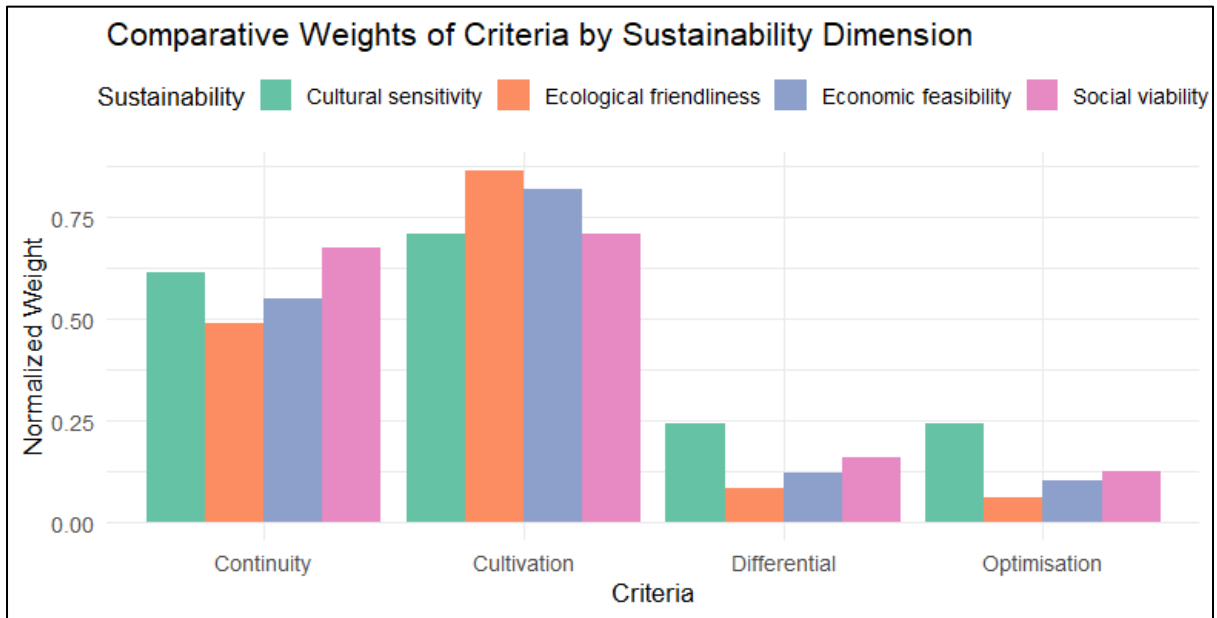


Figure 14: Sensitivity of Overall Sustainability Rank by Dimension ($\pm 20\%$ Variation)

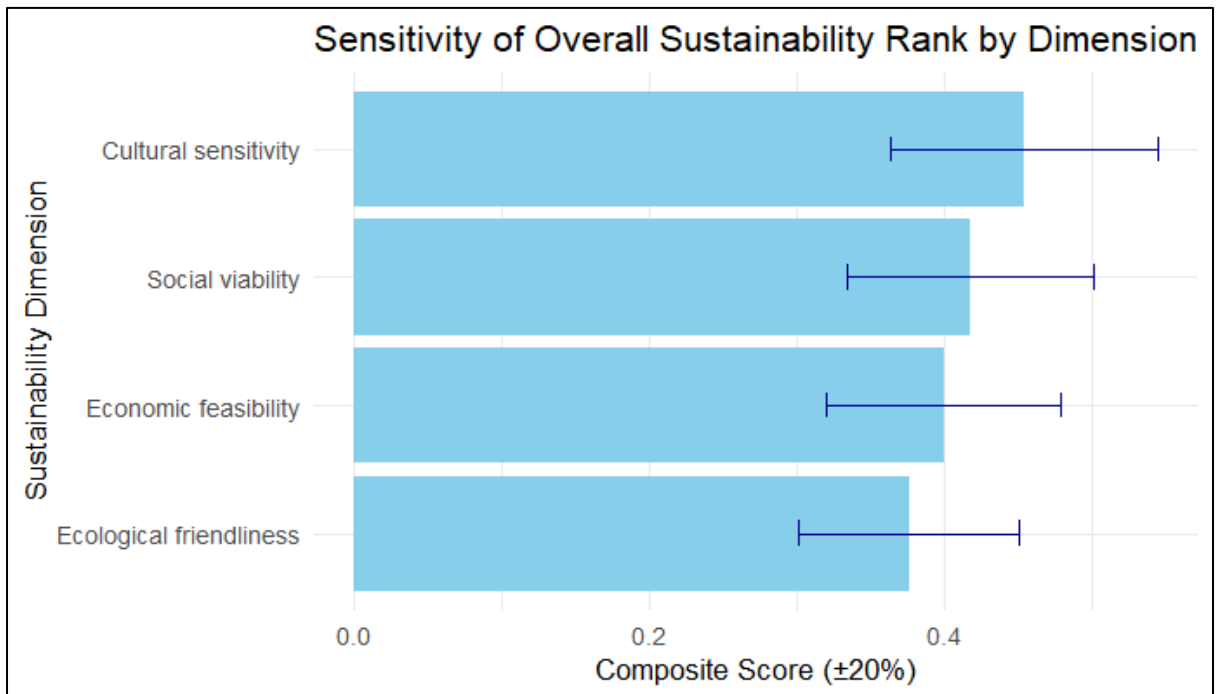


Figure 15: Correlation Heatmap of Sustainability Dimensions

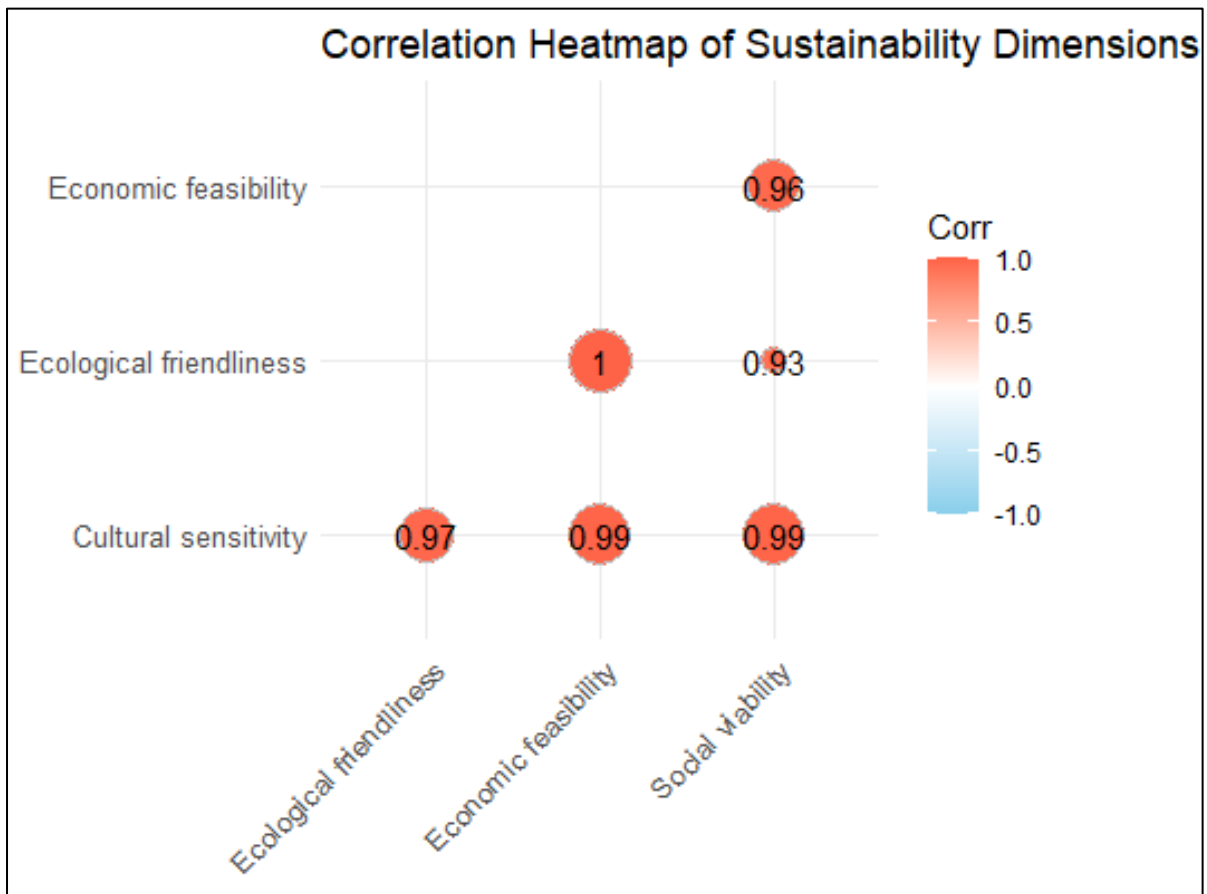


Figure 16. Relative Contributions of Sustainability Dimensions to Overall Performance

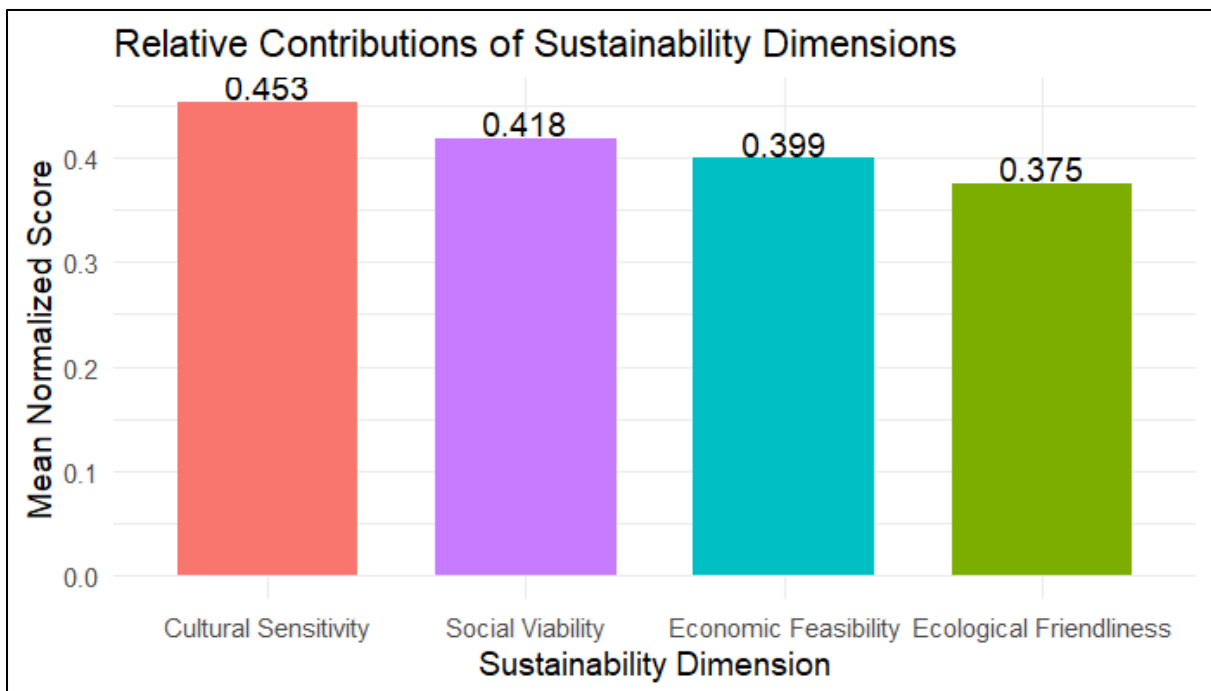
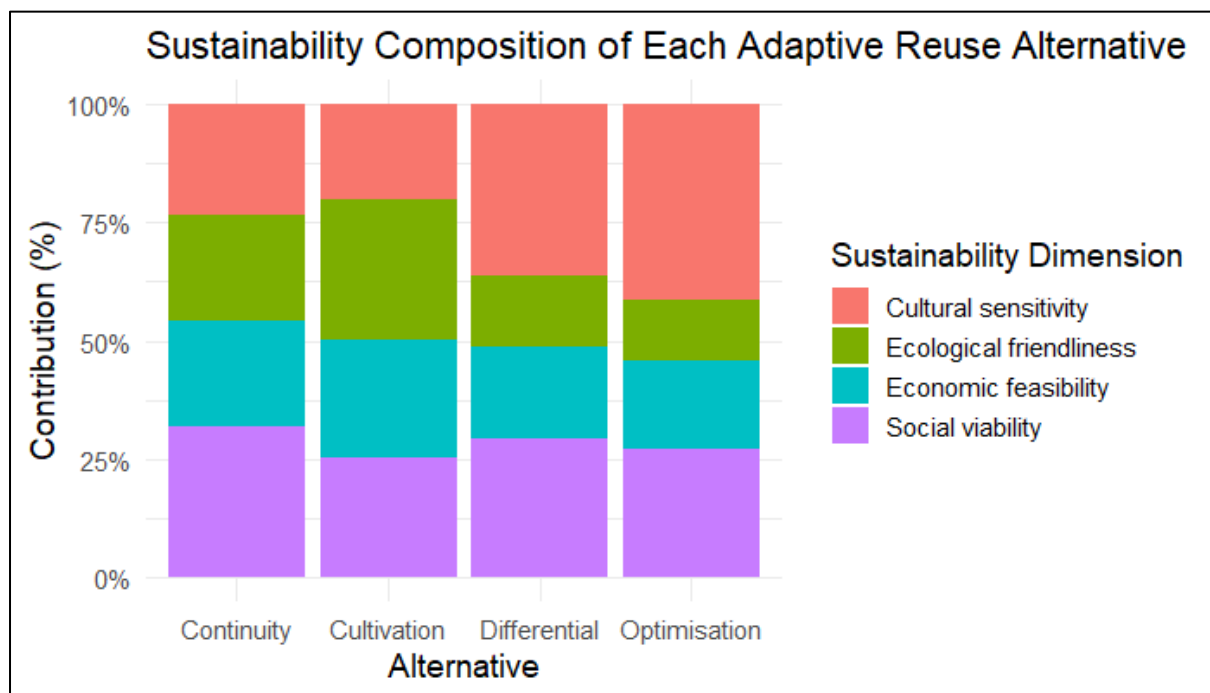


Figure 17. Sustainability Composition of Each Adaptive Reuse Alternative



Appendix C: Tables of Objectives, Indicators, and Evaluation Results

This appendix presents detailed tables used in the analysis, including:

- Objectives, criteria, and indicators with measurement scales (Table 1)
- Mapping of indicator abbreviations (Table 2)
- Sustainability dimensions and indicator calculation guidance (Table 3)
- Weighting results (Table 4)
- TOPSIS ranking and sensitivity analysis outputs (Tables 5–8)

Each table provides transparent data support for the main analyses discussed in the report.

Table 1. Objectives, criteria, indicators and evaluation scales for adaptive re-use of abandoned and dilapidated wooden heritage.

<i>Dimension</i>	<i>Objective (No.)</i>	<i>Criteria (ID)</i>	<i>Indicator description</i>	<i>Evaluation scale</i>
<i>Heritage Continuity</i>	1. Safeguard and transmit the authenticity of wooden and zinc fabric	1.1 Structural soundness of timber	1.1.1 Share of primary timber members (posts, beams, trusses) retained after intervention	Cardinal (%) of original building material retained
			1.1.2 The existing functional characteristics of the wooden members are retained	Cardinal (%) of original building material characteristics retained
	2. Revitalize knowledge of local wooden-building traditions	1.2 Functional compatibility with heritage values	1.2.1 Compatibility of new uses with character-defining wooden features (joinery, finishes, spatial order)	Ordinal (5-point expert panel)
			2.1 Community heritage literacy	2.1.1 Participation rate in heritage walks, talks, or carpentry demonstrations linked to the project
<i>Social Cohesion</i>	3. Valorize intangible carpentry heritage	3.1 Narrative interpretation and storytelling	3.1.1 Quality and depth of interpretation of timber craft (exhibits, signage, digital media)	Ordinal (5-point expert panel)
	4. Strengthen social capital through reuse	4.1 Inclusivity breadth	4.1.1 Diversity of user groups (age, gender, ability) engaged in building construction	Cardinal (% diversity index) / Ordinal (5-point expert panel)
			4.2 Neighbourhood activation	4.2.1 Activation of community activities in the building construction process and building usage
<i>Circular & Creative Economy</i>	5. Stimulate local wood-based entrepreneurship	4.3 Co-creation intensity	4.3.1 Stakeholders acting as co-producers (community orgs, artisans, schools)	Ordinal (5-point expert panel)
			5.1 Job creation	5.1.1 Direct jobs created by the adaptive re-use (operation + maintenance + monitoring)
	6. Financially Viability	5.2 Leveraged local co-financing	5.2.1 Ratio of local/private contributions to total project cost	Local contribution (in Euros)
		6.1 Economic value of proposal	6.2 Financial sufficiency and returns	Economic value (in Euros)
		6.1.1 Net Cost of Restoration	6.2.1 Payback period	In number of years

<i>Access & Environmental Resilience</i>	7. Improve universal access and urban connectivity	7.1 Physical and urban accessibility	7.1.1 Accessibility of interior and public interface (ramps, lifts, wayfinding; compliance with standards)	Ordinal (5-point expert panel)	
	8. Increase operational energy self-reliance	8.1 Energy self-sufficiency & demand reduction	8.1.1 Share of annual electricity from on-site renewables or renewable PPAs	Ordinal (5-point expert panel)	
			8.1.2 Reduction of final energy use versus pre-intervention baseline	Cardinal (kWh/m ² ·yr) / Ordinal (5-point expert panel)	
	9. Reduce resource consumption and environmental impacts	9.1 Water efficiency	9.1.1 Reduction in potable water use via recovery/reuse systems	9.1.1 Reduction in potable water use via recovery/reuse systems	Cardinal (% reduction)
				9.2 Bio-/nature-based components	9.2.1 Area of green roofs/walls, rain gardens, or permeable vegetated surfaces delivered
		9.3 Timber reuse & waste avoidance	9.3.1 Mass of construction/demolition waste avoided through salvage and reuse of wood	9.3.1 Mass of construction/demolition waste avoided through salvage and reuse of wood	Ordinal (5-point expert panel)
				9.4 Life-cycle carbon reduction	9.4.1 Reduction in whole-life GHG emissions compared with a code-compliant new build
	10. Regenerate biocultural assets	10.1 Habitat and urban biodiversity	10.1.1 Area of new/restored habitat and biocultural features (e.g., bat boxes, native planting)	Cardinal (m ²)	

Table 2. Mapping of Full Indicator Descriptions to Short Labels Used in Figures

No.	Full Indicator Description	Short Label (Used in Figures)
1.1.1	Share of primary timber members (posts, beams, trusses) retained after intervention	Timber retained
1.1.2	The existing functional characteristics of the wooden members are retained	Wood function
1.2.1	Compatibility of new uses with character-defining wooden features (joinery, finishes, spatial order)	Feature compatibility
2.1.1	Participation rate in carpentry demonstrations linked to the proposal	Carpentry participation
3.1.1	Quality and depth of interpretation of timber craft (through restoration and new construction)	Craft interpretation
4.1.1	Diversity of user groups (age, gender, ability) engaged in building construction	User diversity
4.2.1	Activation of community activities in the building construction process	Community activation

4.3.1	Stakeholders acting as co-producers (community orgs, artisans, schools)	Co-production
5.1.1	Direct jobs created by the adaptive re-use (operation + maintenance + monitoring)	Jobs created
5.2.1	Ratio of local/private contributions to total project cost	Local contribution
6.1.1	Net cost of restoration	Restoration cost
6.2.1	Payback period	Payback period
7.1.1	Accessibility of interior and public interface (ramps, lifts, wayfinding; compliance with standards)	Accessibility
8.1.1	Share of annual electricity from on-site renewables or renewable PPAs	Renewable energy share
8.1.2	Reduction of final energy use versus pre-intervention baseline	Energy reduction
9.1.1	Reduction in potable water use via recovery/reuse systems	Water reduction
9.2.1	Area of green roofs/walls, rain gardens, or permeable vegetated surfaces delivered	Green surfaces
9.3.1	Mass of construction/demolition waste avoided through salvage and reuse of wood	Waste reduction
9.4.1	Reduction in whole-life GHG emissions compared with a code-compliant new building	GHG reduction
10.1.1	Area of new/restored habitat and biocultural features (e.g., bat boxes, native planting)	Habitat restored

Table 3. Mapping of sustainability dimensions, indicator categories, and calculation guidance for multidimensional analysis

	<i>Sustainability Categories / factors / themes</i>	<i>Indicators</i>
<i>Economic feasibility</i>	Financial viability & business model	1.1 Project net present value (NPV) *(cost criterion) *
		1.2 Payback period *(cost criterion) *
	Market activation & mixed-use intensity	1.3 Annual revenue diversification index
	Local value chains & procurement	1.4 Share of spend to local timber/heritage SMEs
	Employment & enterprise	1.5 Direct jobs created (operation + heritage programming)
	Risk & financial resilience	1.6 Debt-service coverage ratio (DSCR)
<i>Ecological friendliness</i>	Energy performance of timber building	2.1 Reduction in final energy use vs. pre-intervention *(cost criterion) *
	On-site renewables / self-sufficiency	2.2 Share of annual electricity from renewables

	Timber conservation & fabric retention	2.3 Percentage of primary timber members retained
	Material circularity (wood salvage & reuse)	2.4 Mass of salvaged timber reused on site
	Construction & demolition waste diverted	2.5 C&D waste diversion rate
	Water performance	2.6 Potable water reduction via reuse/recovery
	Whole-life carbon	2.7 Life-cycle GHG emissions *(cost criterion) *
	Nature-based solutions & biodiversity	2.8 New/rehabilitated green area and habitat features
<i>Social viability</i>	Inclusion & equitable access	3.1 Diversity of users/beneficiaries
	Health, safety & comfort	3.2 post-occupancy comfort and perceived safety
	Accessibility & connectivity	3.3 Universal access compliance
	Community engagement & co-production	3.4 Stakeholders acting as co-producers
	Education & skills	3.5 Heritage carpentry apprenticeships/training
<i>Cultural sensitivity</i>	Place activation & social vibrancy	3.6 Footfall/dwell-time uplift in the block
	Material authenticity of wooden fabric	4.1 Compatibility of interventions with character-defining timber features
	Intangible heritage & craft continuity	4.2 Depth/quality of interpretation of carpentry traditions
	Reversibility & minimal intervention	4.3 Proportion of reversible additions
	Fit-for-purpose (use–heritage coherence)	4.4 Functional compatibility score

Table 4. Table 4.1. Normalized Weights of the Ten Objectives Derived from the Simos Method

	Objective	Score	Weight
1.	Safeguard and transmit the material authenticity of wooden and zinc fabric	8.40	0.153
2.	Revitalize knowledge of local wooden-building traditions	6.08	0.111
3.	Valorize intangible carpentry heritage	5.61	0.102
4.	Strengthen social capital through reuse	6.16	0.112

5. Stimulate local cooperation and independent financing	4.31	0.078
6. Financial Viability	6.12	0.111
7. Improve universal access and urban connectivity	3.63	0.066
8. Increase operational energy self-reliance	4.68	0.085
9. Reduce resource consumption and environmental impacts	6.01	0.109
10. Regenerate biocultural assets	4.00	0.073

Table 5. TOPSIS Evaluation Results by Alternative

Alternative	S^+ (Distance to PIS) ⁸	S^- (Distance to NIS)	Closeness Coefficient (CC)	Rank
Continuity	0.1675	0.2097	0.5560	2
Cultivation	0.1331	0.2656	0.6662	1
Differential	0.2589	0.1294	0.3332	4
Optimisation	0.2656	0.1331	0.3338	3

Table 6. Sensitivity Analysis of TOPSIS Closeness Coefficient under Weight Perturbation

Perturbation	Continuity	Cultivation	Differential	Optimisation
-20%	0.4300	0.4851	0.3381	0.3124
-10%	0.4300	0.4851	0.3381	0.3124
0%	0.4300	0.4851	0.3381	0.3124
10%	0.4300	0.4851	0.3381	0.3124
20%	0.4300	0.4851	0.3381	0.3124

Table 7. Weighted Indicator-Level Performance by Alternative

Indicator No.	Indicator Name	Continuity	Cultivation	Differential	Optimisation
1.1.1	Share of primary timber members (posts, beams, trusses) retained after intervention	0.1	0.1	0.04	0.03
1.1.2	The existing functional characteristics of the wooden members are retained	0.1	0.1	0.04	0.04
1.2.1	Compatibility of new uses with character-defining wooden features (joinery, finishes, spatial order)	0.09	0.11	0.04	0.04
2.1.1	Participation rate in carpentry demonstrations linked to the proposal	0.07	0.08	0.02	0.02
3.1.1	Quality and depth of interpretation of timber craft (through restoration and new construction)	0.06	0.08	0.02	0.02

⁸ S^+ and S^- represent the Euclidean distances of each alternative from the Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS), respectively (Hwang & Yoon, 1981, "Multiple Attribute Decision Making: Methods and Applications," Springer).

4.1.1	Diversity of user groups (age, gender, ability) engaged in building construction	0.08	0.08	0.02	0.02
4.2.1	Activation of community activities in the building construction process	0.08	0.08	0.02	0
4.3.1	Stakeholders acting as co-producers (community orgs, artisans, schools)	0.08	0.08	0.02	0.02
5.1.1	Direct jobs created by the adaptive re-use (operation + maintenance + monitoring)	0.04	0.06	0.01	0.01
5.2.1	Ratio of local/private contributions to total project cost	0.04	0.07	0	0
6.1.1	Net Cost of Restoration	0.09	0.11	0.03	0.02
6.2.1	Payback period	0.07	0.11	0.01	0.01
7.1.1	Accessibility of interior and public interface (ramps, lifts, wayfinding; compliance with standards)	0.04	0.04	0.02	0.02
8.1.1	Share of annual electricity from on-site renewables or renewable PPAs	0.06	0.06	0	0
8.1.2	Reduction of final energy use versus pre-intervention baseline	0	0	0	0
9.1.1	Reduction in potable water use via recovery/reuse systems	0	0	0	0
9.2.1	Area of green roofs/walls, rain gardens, or permeable vegetated surfaces delivered	0	0.11	0	0
9.3.1	Mass of construction/demolition waste avoided through salvage and reuse of wood	0.08	0.08	0	0
9.4.1	Reduction in whole-life GHG emissions compared with a code-compliant new building	0	0	0	0
10.1.1	Area of new/restored habitat and biocultural features (e.g., bat boxes, native planting)	0	0.07	0	0

Table 8. Top Contributing Indicators and Best-Performing Alternatives by Objective

<i>Objective</i>	<i>Top-Contributing Indicator</i>	<i>Highest Weighted Value</i>	<i>Best-Performing Alternative</i>	<i>Interpretation</i>
<i>Safeguard and transmit the material authenticity of wooden and zinc fabric</i>	Feature compatibility	0.109 (Cultivation)	Cultivation	Strong emphasis on compatible material integration and preservation of authentic wooden fabric.
<i>Revitalize knowledge of local wooden-building traditions</i>	Carpentry participation	0.084 (Cultivation)	Cultivation	High engagement of artisans and local trainees reflects cultural

<i>Valorize intangible carpentry heritage</i>	Craft interpretation	0.078 (Cultivation)	Cultivation	transmission of craftsmanship. Effective narrative and interpretive reuse of traditional carpentry techniques.
<i>Strengthen social capital through reuse</i>	Community activation	0.078 (Cultivation & Continuity)	Cultivation / Continuity	Active community participation and social inclusion during the reuse process.
<i>Stimulate local cooperation and independent financing</i>	Local contribution	0.070 (Cultivation)	Cultivation	Greater reliance on local/private co-financing enhances project ownership.
<i>Financially viability</i>	Payback period	0.111 (Cultivation)	Cultivation	Balanced economic return and cost recovery potential ensure long-term feasibility.
<i>Improve universal access and urban connectivity</i>	Accessibility	0.043 (Cultivation & Continuity)	Cultivation / Continuity	Both alternatives perform equally, showing consistent attention to inclusive design.
<i>Increase operational energy self-reliance</i>	Renewable energy share	0.060 (Cultivation & Continuity)	Cultivation / Continuity	Renewable energy integration remains moderate but balanced.
<i>Reduce resource consumption and environmental impacts</i>	Green surfaces	0.109 (Cultivation)	Cultivation	Cultivation excels in integrating green infrastructure and waste-reuse strategies.
<i>Regenerate biocultural assets</i>	Habitat restored	0.073 (Cultivation)	Cultivation	Incorporates ecological and cultural restoration features (habitat and biodiversity).

Appendix D: Data Analysis Procedures and Computation Sheets

This appendix documents the analytical workflow, including data normalization steps, weighting calculations (Simos method), and TOPSIS computation matrices. It may also include R code snippets or screenshots demonstrating how results were generated to ensure replicability.

Evaluation and Selection of Optimal Solution Using MCDA

After defining the adaptive reuse objectives, developing four architectural alternatives, and establishing evaluation indicators in Phase 1, Phase 2 focuses on the systematic evaluation and selection of the optimal adaptive reuse solution using a Multi-Criteria Decision Analysis (MCDA) approach. This phase is critical, as it integrates stakeholder perceptions of heritage authenticity with sustainability, social, cultural, and economic objectives, ensuring participatory, evidence-based, and robust decision-making.

Multicriteria Evaluation

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Hwang & Yoon, 1981) was chosen for the evaluation because it:

- Allows integration of qualitative and quantitative data, critical in early phases where design alternatives may be conceptual or partially defined.
- Evaluates alternatives based on their closeness to the Positive Ideal Solution (PIS) and distance from the Negative Ideal Solution (NIS), capturing both opportunity and risk (Yoon, 1980; Balioti et al., 2018).
- Facilitates stakeholder participation through weighted criteria derived from the Simos card-ranking method (Simos, 1990; Roy & Słowiński, 2013).
- Offers a transparent, efficient, and easily interpretable framework suitable for iterative co-evaluation.
- Is adaptable: additional alternatives or indicators can be incorporated without changing the underlying procedure (Pinzon Amorocho & Hartmann, 2022).

Order of Preference by Similarity to Ideal Solution (TOPSIS) Evaluation Steps

Performance Matrix

Each alternative (Differential, Continuity, Cultivation, Optimisation) was evaluated against the criteria and indicators established in Phase 1. Qualitative criteria were converted into numerical scores using stakeholder judgment.

Normalization of Decision Matrix

To make values comparable across different scales:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}}$$

Where:

- r_{ij} = normalized value of alternative i for criterion j
- x_{ij} = original performance score
- m = number of alternatives

Weighted Normalized Matrix

Weights were assigned to criteria using the **Simos weighting method**⁹, which converts stakeholder ordinal rankings into cardinal weights. If w_j is the weight of criterion j , the weighted normalized score is:

$$v_{ij} = w_j \cdot r_{ij}$$

Step 4: Identify Positive and Negative Ideal Solutions

$$A^+ = \{v_1^+, v_2^+, \dots, v_n^+\}, v_j^+ = \max(v_{ij})$$

$$A^- = \{v_1^-, v_2^-, \dots, v_n^-\}, v_j^- = \min(v_{ij})$$

Step 5: Euclidean Distance from Ideal Solutions

$$S_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2}, S_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2}$$

Step 6: Closeness Coefficient and Ranking

$$CC_i = \frac{S_i^-}{S_i^+ + S_i^-}, 0 \leq CC_i \leq 1$$

Where CC_i = relative closeness to the ideal solution. Alternatives are ranked based on decreasing CC_i , with higher values indicating preferred solutions.

⁹ The Simos method (Simos, 1990) uses a card-ranking procedure to translate stakeholder ordinal preferences into numerical weights, enabling transparent and participatory assignment of importance to objectives.

Scenario Evaluation: Sensitivity Analysis

To assess the robustness of rankings:

- **Weights Adjustment:** Criterion weights were varied systematically ($\pm 10\text{--}20\%$) to reflect potential subjectivity and uncertainty.
- **Ranking Recalculation:** TOPSIS was re-applied to evaluate changes in alternative preference order.
- **Outcome:** Identified critical criteria influencing rankings and assessed stability of results, ensuring a robust, participatory evaluation.

Stakeholder Validation and Participatory Decision-Making

Following the TOPSIS ranking and sensitivity analysis:

- Stakeholders reviewed the alternative rankings in a **co-design workshop**, reflecting on trade-offs between authenticity, sustainability, and functional objectives.
- Iterative feedback allowed refinement of criteria, weights, and final selection, enhancing social acceptance and legitimacy of the chosen adaptive reuse solution.

Rationale for Choosing TOPSIS

The TOPSIS method was selected for this study because it effectively supports the evaluation of multiple adaptive reuse alternatives across diverse criteria. It combines quantitative and qualitative information, allows stakeholder participation, and produces clear, reproducible results. Its flexibility and simplicity make it particularly suitable for participatory, evidence-based decision-making in heritage reuse projects.

- **Multidimensional evaluation:** Supports integration of multiple criteria (cultural, social, economic, environmental).
- **Qualitative and quantitative inclusion:** Captures both early conceptual ideas and later detailed project data.
- **Transparency and participation:** Weights can be derived from stakeholders; results are clear and reproducible.
- **Iterative adaptability:** New alternatives or indicators can be integrated without changing the workflow.
- **Mathematical simplicity:** Euclidean distance-based calculation is simple, easy to understand, and facilitates robust decision-making.

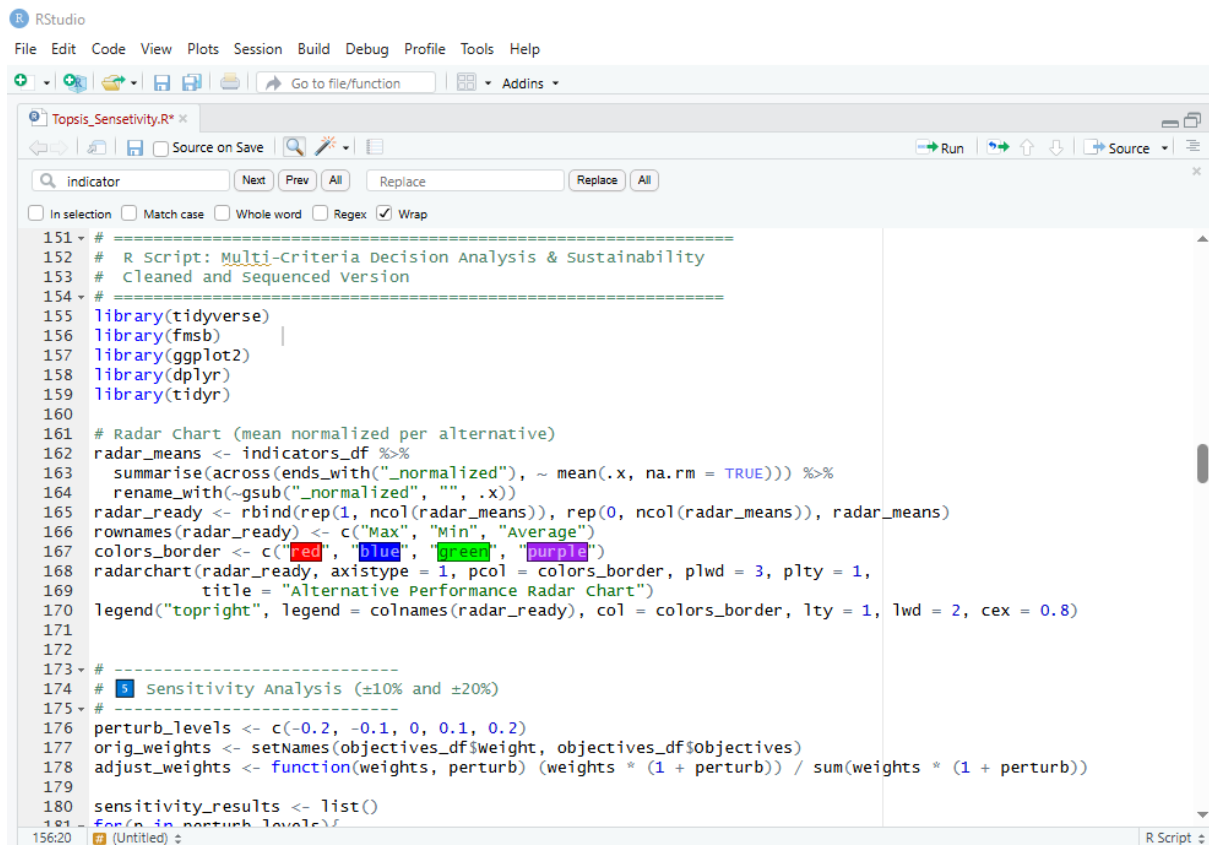
Data Analysis Process

In R (Script-Based Analysis):

Data analysis was performed using R software to ensure transparency and reproducibility.

The script included the following key steps:

1. Data import and cleaning – Organizing stakeholder weights and performance indicator values.
2. Normalization – Standardizing indicator values to a comparable scale (benefit or cost criteria).
3. Weight application – Multiplying normalized values by the Simos-derived weights.
4. PIS and NIS determination – Identifying the *Positive Ideal Solution (PIS)* and *Negative Ideal Solution (NIS)* for each criterion.
5. Closeness Coefficient (CC) calculation – Computing the relative closeness of each alternative to the ideal solution.
6. Ranking – Generating the final preference order of adaptive reuse alternatives based on CC values.



```
151 # =====
152 # R Script: Multi-Criteria Decision Analysis & sustainability
153 # Cleaned and Sequenced Version
154 # =====
155 library(tidyverse)
156 library(fmsb)
157 library(ggplot2)
158 library(dplyr)
159 library(tidyr)
160
161 # Radar Chart (mean normalized per alternative)
162 radar_means <- indicators_df %>%
163   summarise(across(ends_with("_normalized"), ~ mean(.x, na.rm = TRUE))) %>%
164   rename_with(~gsub("_normalized", "", .x))
165 radar_ready <- rbind(rep(1, ncol(radar_means)), rep(0, ncol(radar_means)), radar_means)
166 rownames(radar_ready) <- c("Max", "Min", "Average")
167 colors_border <- c("red", "blue", "green", "purple")
168 radarchart(radar_ready, axistype = 1, pcol = colors_border, plwd = 3, plty = 1,
169           title = "Alternative Performance Radar Chart")
170 legend("topright", legend = colnames(radar_ready), col = colors_border, lty = 1, lwd = 2, cex = 0.8)
171
172
173 # -----
174 # [5] Sensitivity Analysis (±10% and ±20%)
175 # -----
176 perturb_levels <- c(-0.2, -0.1, 0, 0.1, 0.2)
177 orig_weights <- setNames(objectives_df$weight, objectives_df$objectives)
178 adjust_weights <- function(weights, perturb) (weights * (1 + perturb)) / sum(weights * (1 + perturb))
179
180 sensitivity_results <- list()
181 for(p in perturb_levels){
```

In Excel (Manual Calculation):

The same analytical workflow was replicated in Excel to validate R outputs. This included:

- Weight calculation using Simos method (ordinal-to-cardinal conversion).
- Normalization of indicators using benefit/cost criteria formulas.
- Weighted score computation across all objectives.
- PIS and NIS identification and distance measurement using Euclidean distance.
- Closeness Coefficient (CC) calculation and final ranking of alternatives.

Data Analysis and Computation Sheets

	D	K	L	M	N	O	P	Q
1	Indicator	VectorLength4alternatives	Continuity_normalized	Cultivation_normalized	Differential_normalized	Optimisation_normalized	Weighted_Continuity	Weighted_Cultivation
2	1.1.1 Share of primary tr	1.5	0.66666667	0.66666667	0.26666667	0.2	0.101818182	0.101818182
3	1.1.2 The existing functi	1.523154621	0.656532164	0.656532164	0.262612866	0.262612866	0.100270367	0.100270367
4	1.2.1 Compatibility of ne	7	0.571428571	0.714285714	0.285714286	0.285714286	0.087272727	0.109090909
5	2.1.1 Participation rate in	6.557438524	0.609994281	0.762492852	0.15249857	0.15249857	0.067432095	0.084290119
6	3.1.1 Quality and depth c	6.557438524	0.609994281	0.762492852	0.15249857	0.15249857	0.062219417	0.077774271
7	4.1.1 Diversity of user gr	7.211102551	0.693375245	0.693375245	0.138675049	0.138675049	0.077658027	0.077658027
8	4.2.1 Activation of comm	7.141428429	0.700140042	0.700140042	0.140028008	0	0.078415685	0.078415685
9	4.3.1 Stakeholders acting	7.211102551	0.693375245	0.693375245	0.138675049	0.138675049	0.077658027	0.077658027
10	5.1.1 Direct jobs created	36.74234614	0.544331054	0.816496581	0.136082763	0.136082763	0.042655761	0.063983641
11	5.2.1 Ratio of local/privat	22360.67977	0.447213595	0.894427191	0	0	0.035045284	0.070090567
12	6.1.1 Net Cost of Restora	1033876.201	0.85	1	0.283333333	0.2125	0.094581818	0.111272727
13	6.2.1 Payback period	42.82522621	0.6	1	0.1	0.1	0.066763636	0.111272727
14	7.1.1 Accessibility of inte	7.615773106	0.656532164	0.656532164	0.262612866	0.262612866	0.043331123	0.043331123
15	8.1.1 Share of annual ele	7.071067812	0.707106781	0.707106781	0	0	0.060168359	0.060168359
16	8.1.2 Reduction of final e	7.071067812	0	0	0	0	0	0
17	9.1.1 Reduction in potab	7.071067812	0	0	0	0	0	0
18	9.2.1 Area of green roofs	120	0	1	0	0	0	0.109272727
19	9.3.1 Mass of constructio	5.656854249	0.707106781	0.707106781	0	0	0.077267486	0.077267486
20	9.4.1 Reduction in whole	0.644204936	0	0	0	0	0	0
21	10.1.1 Area of new/resto	200	0	1	0	0	0	0.072727273

Weights were assigned to criteria using the Simos weighting method

Objectives	Score	Weight
1. Safeguard and transmit the material authenticity of wooden and zinc fabric	8.4	0.152727273
2. Revitalize knowledge of local wooden-building traditions	6.08	0.110545455
3. Valorize intangible carpentry heritage	5.61	0.102
4. Strengthen social capital through reuse	6.16	0.112
5. Stimulate local cooperation and independent financing	4.31	0.078363636
6. Financially Viability	6.12	0.111272727
7. Improve universal access and urban connectivity	3.63	0.066
8. Increase operational energy self-reliance	4.68	0.085090909
9. Reduce resource consumption and environmental impacts	6.01	0.109272727
10. Regenerate biocultural assets	4	0.072727273

The 4x2 results are four distances to PIS and four distances to NIS, one pair per alternative.

Alternative	S_Plus_DistanceToPIS	S_minus_DistanceToNIS	Closeness_Coefficient	Rank
Continuity	0.167458615	0.209725702	0.556029751	2
Cultivation	0.133070098	0.265560218	0.666181691	1
Differential	0.258888013	0.129375731	0.333216102	4
Optimisation	0.265560218	0.133070098	0.333818309	3

Appendix E: Comprehensive Data Table of Objectives, Criteria, Dimensions, Indicators, and Survey Results

This appendix presents a detailed compilation of all data used in the multi-criteria decision-making (MCDM) analysis. The table integrates the hierarchical structure of the assessment, linking overall objectives, evaluation criteria, sustainability dimensions, and specific indicators with the corresponding stakeholder survey results.

The table serves as a foundational reference for the analytical stages of the study, including normalization, weighting, and the TOPSIS computation of the Closeness Coefficient (CC). It demonstrates how stakeholder perceptions and quantitative data were aligned to evaluate adaptive reuse alternatives systematically.

Table Contents:

- **Objective:** The overarching goal of the sustainability assessment.
- **Criteria:** The key evaluative components under each objective.
- **Dimension:** The four sustainability dimensions (Economic, Social, Cultural, and Environmental).
- **Indicator:** The measurable variables under each criterion.
- **Survey Results:** Mean stakeholder scores representing perceived performance of each alternative for every indicator.

Appendix F: Stakeholder Consultation Instruments

This section includes tools and materials used for stakeholder engagement, such as:

- Simos card-ranking templates
- Interview or focus group discussion (FGD) guides
- Stakeholder mapping matrix and participation summary