LCA and AHP-Based Sustainability Assessment for Heritage Building Renovation

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Abstract. Addressing the lack of high-precision Building Information Modeling (BIM) and structured archives for heritage buildings, this study proposes a decision-making framework integrating Life Cycle Assessment (LCA) and Analytic Hierarchy Process (AHP) derived from 2D CAD drawings. By extracting geometric features via a segmented section method and applying historical construction standards, unstructured information is transformed into standardized LCA material flows. Three restoration schemes—minimal intervention (A1), traditional (A2), and composite reinforcement (A3)—are evaluated using the Ecoinvent database. AHP is then employed to synthesize LCA results with qualitative criteria, including heritage protection, structural performance, and economic efficiency. Results indicate the framework effectively quantifies strategy benefits, providing a transparent basis for sustainable heritage protection despite data scarcity.

Keywords: LCA · AHP · Historical Buildings · Unavailable data · Sensitivity Analysis · Structural Restoration · HBIM-light

1 Introduction

The construction industry consumes massive resources and accounts for approximately 35% of EU carbon emissions throughout its life cycle. Addressing implicit carbon issues in the production and transport of building materials is increasingly critical for policymakers and academia [1]. In this context, protecting historical religious buildings faces a dual challenge: adhering to heritage authenticity while responding to entire life-cycle carbon reduction requirements [2]. Natural disasters, such as earthquakes, exacerbate this conflict, as post-disaster reinforcement often faces resource shortages and time urgency, leading to the use of high-impact carbon materials. While Building Information Modeling (BIM) and Life Cycle Assessment (LCA) have advanced environmental load quantification, existing HBIM-LCA paths remain highly dependent on high-precision parametric models and complete databases. In heritage-rich regions like Italy, many sites lack such data, relying instead on basic 2D CAD drawings that lack the parametric information required for BIM. This "digital gap" hinders the direct transfer of mainstream HBIM-LCA processes into practice.

This paper proposes a framework to overcome this "data bottleneck" by establishing a direct mapping mechanism from unstructured 2D CAD geometric data to material environmental properties. This approach enables accurate environmental load calculation

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for complex historical components without high-precision BIM support. The framework integrates LCA with the Analytic Hierarchy Process (AHP) to evaluate restoration schemes—such as those for the Church of Beata Vergine della Cintura of San Giovanni in Persiceto, Italy—balancing structural safety, ecological sustainability, and cultural authenticity. This research provides a methodological basis for low-carbon restoration decisions within data-scarce environments.

2 Literature Review

The concept of LCA has grown into a fully developed mechanism in environmental performance analysis of the new buildings. In recent years, scholars have begun to adapt it into the field of historical building conservation. Karglou et al. [3] applied LCA to the conservation intervention assessment of traditional architectural heritage and found that material selection and repair techniques have a significant impact on environmental performance. Franzoni et al. [4] further extended the LCA method to the environmental impact assessment of historical building cleaning procedures, revealing the environmental load generated by the conservation operation itself. However, Akşar et al. [5] pointed out through bibliometric analysis that although research on historical building LCA is on the rise, compared with new buildings, historical buildings have complex structures and environmental data on traditional materials are often missing. This "non-standardized" characteristic poses significant challenges to the quantitative application of LCA in historical heritage.

In order to solve this data extraction problem, the mainstream trend in recent years has been to integrating BIM as a bridge to LCA. This "BIM-LCA" integration path theoretically provides data-driven decision support for conservation projects. For example, Al-Zrigat [6] achieved a parametric assessment of the energy performance of historic buildings by integrating the ISO 14040 principle with spatial ETL technology. Valipour et al. [7] quantified the carbon reduction potential (approximately 30%) of optimized material combinations in the restoration of historic buildings by integrating BIM, LCA, and multi-criteria decision-making models. However, this method, which relies on high-precision three-dimensional models, is facing a serious "information gap" in actual engineering. Shehata et al. [8] pointed out through SWOT analysis that the high modeling cost and the scarcity of historical data constitute a very high technical threshold. In particular, for a large number of historic buildings with only basic two-dimensional CAD drawings, it is not realistic to mandate a high-precision BIM modeling. This leads to a huge "digital divide" between "basic CAD drawings" and "structured LCA evaluation".

On the other hand, even if the problem of basic data extraction is solved, the renovation and regeneration of historical buildings still face complex value trade-offs. Heritage protection not only needs to consider environmental sustainability, but also must take into account cultural authenticity and economic feasibility. For this reason, the multi-criteria decision-making (MCDA) method has been widely introduced. For example, Ferretti [9] used the AHP to transform abstract cultural values into an operational evaluation system to explore the priority ranking of adaptive reuse of heritage sites. Furthermore, Abastante et al. [10] introduced the SRF-II method to compare different hypotheses for the adaptive reuse of iconic historical buildings, emphasizing the importance of ranking

criteria based on diverse stakeholder perspectives. However, existing AHP studies often overemphasize qualitative socio-cultural indicators, and environmental performance is usually only regarded as a rough secondary consideration, lacking a systematic combination with the precise quantitative data of LCA. Based on the above-mentioned real pain points, this paper aims to provide an alternative for the real engineering scenario of "data limitation". This paper proposes an integrated "CAD-LCA-AHP" evaluation framework that explores a lightweight path to extract data directly from basic two-dimensional CAD drawings to LCA, and then use the AHP decision model to deeply integrate the objective quantitative data produced by LCA with subjective qualitative principles such as cultural heritage protection. This framework aims to provide a multi-dimensional evaluation system for the renovation and regeneration of historical religious buildings that takes into account both feasibility and scientific transparency.

3 Methodology

This study constructs a progressive comprehensive evaluation workflow for the restoration of historical buildings concerning LCA evaluation. This methodology aims to overcome the limitations of single-dimensional evaluation and is divided into four core stages: the first stage is data acquisition, which involves extracting architectural geometry and material information from basic CAD drawings; the second stage is scheme generation, which involves developing different renovation strategies based on the extracted information; the third stage is objective quantification, which uses LCA to accurately calculate the environmental performance of each restoration scenario; and the fourth stage is comprehensive decision-making, which introduces AHP to construct a multi-criteria evaluation system. This framework focus on a decision-making view of four dimensions, including heritage conservation value (A), technical structural performance (B), environmental sustainability (C), and economic feasibility (D). By scientifically allocating weights, it ultimately identifies the overall optimal restoration scheme.

3.1 Material Flow Characterization: A Geometric Data Extraction Process Based on 2D Drawings

Given the general lack of high-precision Building Information Models (HBIMs) for historic heritage buildings, this study proposes a method for quantity extraction and data conversion based on 2D CAD drawings to address the challenge of converting unstructured drawings into LCI material flow data.

First, in the geometric information acquisition stage, for irregular walls and complex vault systems in historic masonry structures, this study employs a segmented section method to compile a Quantity Take-off (QTO): The characteristic cross-sectional area (Ai) of each component is extracted in the CAD environment, and its geometric volume is calculated by combining it with the measured height or thickness (Hi). Subsequently, by combining regional historical building construction codes and literature, corresponding physical parameters (such as brick density, mortar mix ratio, etc.) are matched to the above geometric volumes, thereby converting the geometric volumes of the components into the actual mass (kg) of the materials. Lastly, the standardized mass data

is transformed and converted and integrated with the LCI database. This whole procedure, including 2D geometric breaking out to material mass conversion to environmental influence correspondence, is essentially addresses the assessment challenge posed by the absence of 3D structure, which has supplied trusted groundwork knowledge concerning the next correct determination of the environmental load of historic buildings.

The logical progression from geometric reduction to LCA integration is summarized in Fig. 1.

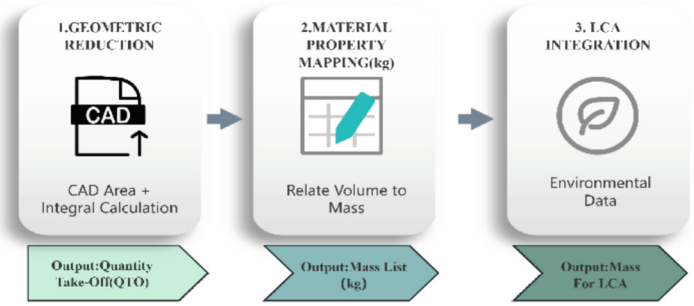

Fig. 1. Integration path of historical building quantity accounting and LCI

3.2 Repair Scenarios

To substantially contrast the overall benefits of the intervention strategies in a multidimensional assessment system, this work selected three representative scheme backgrounds of historical building restoration (A1-A3) as the objects of analysis to the decision-making criteria in the subsequent stages:

Option 1 (A1) - Minimal Intervention (Existing Baseline): This alternative promotes the principle of minimal intervention; only the routine preventative level of intervention (surface treatment and crack grouting) would be done. Option A1 preserves the building's material authenticity to the greatest extent possible, but essentially does not alter the existing structural stress state and cannot effectively improve seismic performance. It is mostly used in this paper as a reference point in making the comparison of the environmental and technical merits of the other structural reinforcement structures.

Option 2 (A2) - Traditional Retrofitting: This alternative is the typical engineering practice during the last several decades, this objective enhances safety primarily by increasing structural rigidity. Some of the specific measures involve the installation of reinforced concrete (RC) ring beam, steel bracing, or a massive tie rod. Although this alternative has great potential to boost the final bearing capacity of the building, it usually involves introducing large masses of new high-energy materials (high embodied carbon content) and involves much destruction of the historical texture. Reversibility of the intervention measures is also not good and the physical compatibility of materials is poor.

Option 3 (A3) - Novel Composite Material Reinforcement: Scheme presents an advanced composite materials-based repair technology, which is a low-intervention, high-toughness type named as FRCM [11]. Seismic ductility by laying high-performance

mesh onto the surface of the masonry may be attained without materially altering the initial stiffness distribution of the structure. Moreover, the lightweight and thinness properties of composite materials not only significantly reduce the implicit carbon emissions of substances, but also guarantee the extensive reversibility of the reinforcing actions, and consequently, it provides a greater ratio between the structural performance, environmental sustainability and the safeguarding of heritage.

3.3 Environmental Performance Quantitative Evaluation Framework

In this paper, the total mass (kg) of the different component materials (including mortar, reinforcing fibers, and steel) obtained in the last step was mapped to the internationally accepted Ecoinvent 3.10 database. Through connecting with the relevant background dataset and extracting. Environmental emission factors, the conversion process of the engineering physical quantities into the environmental load data was completed.

During the Life Cycle Impact Assessment (LCIA) stage, three primary quantitative indicators were selected to address global warming and resource depletion:

Global Warming Potential (GWP): Used to compute the greenhouse gas emissions (i.e., carbon footprint) of each restoration scheme over its life cycle.

Acidification Potential (AP): Evaluates the acidification burden on local soil and water conditions resulting from acid gas emissions (e.g., SO_2 and NO_x) during the manufacturing, transportation, and construction phases.

Resource Utilization (RU): Focuses on the concentration of primary resources within the materials and their recyclability at the end-of-life stage, thereby reflecting the circular economy benefits of each scheme.

The outputs of these three indicators serve as direct quantitative inputs for the subsequent AHP multi-criteria decision-making model. This ensures that the selection of the optimal solution is supported by objective data within the environmental sustainability dimension.

3.4 Construction of Decision Model: AHP Weight Allocation and Comprehensive Evaluation.

The preservation and renovation of historic buildings involve a complex interplay among structural safety, environmental conservation, and cultural heritage preservation. To balance these needs scientifically, this study employs an integrated AHP-Weighted Scoring model. While AHP is employed to determine the hierarchical weights of the criteria—Heritage Preservation Value (A), Technical Structural Performance (B), Environmental Sustainability (C), and Economic Feasibility (D)—a direct weighted-sum method aggregates the performance of alternatives. This hybrid approach allows for the seamless integration of quantitative LCA results and qualitative expert ratings.

During the weight allocation stage was done by the authors, addressing their experience in construction renovation projects, architectural heritage conservation, structural engineering, and sustainable design. The weight allocation was performed by pairwise comparisons for each appraisal standard using Saaty's 1–9 scale. Once the judgment matrices were constructed and consistency ratios (CR) were verified to be below 0.1,

the final weights were computed. At last, In the final evaluation step, the individual performance of each restoration scheme was measured. To ensure transparency and replicability, the scores for environmental indicators were obtained by linearly normalizing the absolute LCA results into a 1–10 scale (see Table 6), where the lowest environmental impact corresponds to a score of 10. Qualitative scores were based on standardized performance rubrics. This scientific integration of environmental load data and qualitative heritage protection assessments ensures a robust basis for selecting the optimal transformation strategy.

4 Case Study

4.1 Site Context

This study employs a case study of the Beata Vergine della Cintura Church of San Giovanni in Persiceto, Italy. The church is a common historical masonry religious construction, the backbone of which is made up of load-bearing brick walls and complicated interlocked vaults. The building needs structural reinforcement and performance improvement as a result of a long-term combination of natural weathering factors and possible risks of earthquakes.

The project, however, had a common problem of data constraints in the initial phases of the redesign procedure. The church does not have a high-precision HBIM, as most of the local heritage sites that have not been overly developed in terms of commercialization have not received such models. Current technical archives have rudimentary two-dimensional drawings in CAD and do not have systematic records of materials' physical properties. This huge discrepancy between the fact that spatial geometry is highly complex and the underlying data is low-structured is the very reality of numerous small and medium-sized historical building renovation projects today. Thus, this church was a perfect place where it was necessary to check how the offered "CAD-LCA-AHP" light-weight embedded assessment framework is feasible.

4.2 Geometric Representation and Material Quantification

In this research, the unit of analysis used in extracting the quantity of the longitudinal aspect is the U-shaped section of the part of the wall on the north side of the church which has a total length of approximately 12.95 m. Asymmetrical door and window openings have been added to this wall, and the top elevation reaches a maximum of 11.40 m (see Fig. 2). Despite these geometric complexities, this section is considered a representative structural unit of the entire church nave. It encompasses the standard masonry patterns, opening modules, and typical degradation characteristics found throughout the longitudinal walls. Since the material composition and load-bearing logic are consistent across the main body of the building, the findings derived from this typical section can be generalized to the entire structure. Due to the use of an irregular geometric form of the masonry walls of historical buildings, the use of complex openings on the facade, and the complex shape of the overall estimation processes lead to serious errors. Thus, to complete the calculation correctly, the segmented section method is used in this research:

the geometric features of the wall section are subdivided into many regular blocks and the net cross-sectional area of each block is calculated and multiplied by the average wall thickness, and the volume of openings is deducted to get the actual amount of material in this irregular longitudinal wall.

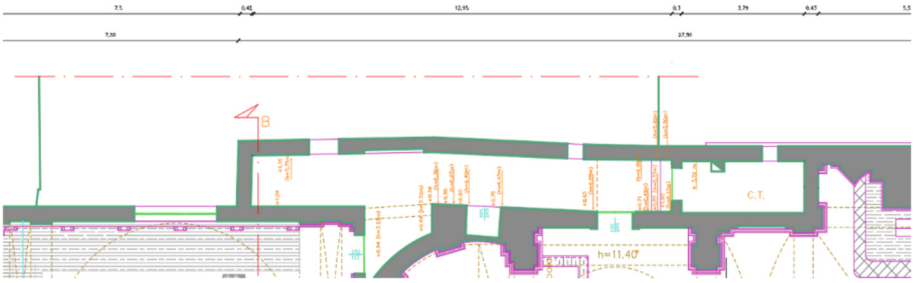

Fig. 2. Floor plan used for QTO of the B. V. della Cintura Church.

Calculation which determines the Gross Volume: L = 12.95m which is the wall length, the average height of the wall is estimated at H ≈11m and assuming a wall thickness of T = 0.8m, representing the typical thickness of an Italian rural church wall:

$$V_{total} = 12.95 \times 11 \times 0.8 \approx 114\,\mathrm{m}^3 \tag{1}$$

Calculation of Window Openings: The volume of the overall opening based on the window distribution given in the CAD drawings is approximately 14 m^3:

$$\mathrm{V_{net}} = 114 - 14 = 100\,\mathrm{m}^3 \tag{2}$$

When the space occupied by the window openings and multiplied by the brick density of 1800 kg/m^3 is subtracted and the total material mass of this unit established as approximately 180 tons. The detailed calculation parameters and resulting mass are summarized in Table 1.

Table 1. Summary of Geometric Dimensions and Mass of Building Components

Category	Parameters	Values	Unit	Remarks/Source
Geometry	Element length (L)	12.95	m	Based on CAD planar surveying
	Average height (H)	11,00	m	Based on drawing annotations
	Wall thickness (T)	0.80	m	Measured from existing masonry
	Gross Volume (V_{total})	114	m^3	L × H × T
Net Volume	Volume of window opening (A_{open})	14	m^3	Geometric extraction from CAD

(*continued*)

Table 1. (*continued*)

Category	Parameters	Values	Unit	Remarks/Source
	Net volume (V_{net})	100.00	m^3	Actual volume after deducting openings
Current Situation	Masonry density (ρ_m)	1,800	kg/m^3	Historical building construction codes
	Total masonry mass (M_m)	180.00	t	Used for LCA baseline calculation

4.3 Quantitative Comparison of Environmental Performance Across Repair Scenarios

In this work, three sets of repair schemes of technical gradients and protection philosophy of a selected 12.95-m exterior wall analysis unit were designed to compare the environmental performance and the structural resilience of diverse intervention strategies. Detailed geometric and material parameters are summarized in Table 2.

Option 1 (A1) - Baseline (Minimum Intervention):
This scheme follows the principle of minimum intervention. Its main measures include lime mortar grouting of existing cracks, partial removal of masonry, and necessary preventative maintenance. In this scheme, except for a very small amount of maintenance materials, the material condition of the original 180 tons of masonry is basically maintained. Although it has the lowest environmental load, it cannot provide additional structural safety guarantees in response to the potential seismic risk in the region.

Option 2 (A2) - Traditional Retrofitting:
This traditional reinforcement scheme incorporates a concrete ring beam with a 0.40m $\times$ 0.30m cross-section. Based on a concrete density of 2,400kg/m^3 and a reinforcement ratio of 100kg/m^3, the total mass increment (ΔM_{A2}) is calculated.

Option 3 (A3) - Advanced Reinforcement (FRCM):
Aligned with circular economy principles, this scheme adopts Fiber Reinforced Cementitious Matrix (FRCM) technology. A 15 mm thick high-performance cement mortar is applied to both sides of the 12.95 m l wall, embedded with carbon fiber mesh. After deducting the three window openings (total area 4.20 m^2), the net reinforced area (A_{net}) is 259.70 m^2. Following Italian engineering standards (CNR) [12], a material loss coefficient of $\alpha = 10\%$ is applied. With a fiber mesh unit weight (ω) of 250 g/m^2, the total incremental mass (ΔM_{A3}) is derived from the mortar matrix (M_{mortar}) and fiber mesh (M_{mesh}).

Table 2. Geometric Calculation and Material Inventory for Restoration Scenarios

Scenario	Core Formula	Parameters & Data Sources	Mass Result
A1: Baseline	$M_{base} = V_{net} \times \rho_m$	$V_{net} = 100\,m^3$	180,000 kg
		$\rho_m = 1800\,kg/m^3$	
A2: Traditional	$\Delta M_{A2} = M_{conc} + M_{steel}$	$M_{Concrete} = V_{concrete} \times \rho_{concrete} = 1.554 \times 2400 = 3729.6\,kg$ (1)	3,885 kg
		$M_{steel} = V_{concrete} \times \rho_{steel} = 1.554 \times 100 = 155.4\,kg$ (2)	
A3: Advanced (FRCM)	$\Delta M_{A3} = M_{mortar} + M_{mesh}$	$M_{mortar} = A_{net} \times t_{total} \times \rho_{mortar} = 259.70 \times 0.03 \times 1800 = 14023.80\,kg$ (3)	14,166.64kg
		$M_{mesh} = A_{net} \times N \times \omega \times (1 + \alpha) = 259.70 \times 2 \times 0.25 \times 0.10 = 142.84\,kg$ (4)	

4.4 System Boundaries for LCA Calculation

This section defines the LCA system boundaries for the north longitudinal wall unit.

A1: Baseline Scenario (Minimum Intervention):

Even though Option A1 is characterized as a maintenance-only approach, it consumes 540.0 kg of materials to deal with centuries of environmental degradation. These materials primarily consist of hydraulic lime (NHL) mortar for localized repairs of deteriorated joints and mineral-based reinforcing agents for strengthening weathered masonry surfaces. Also, 220.00 kg of tap water and 18.00 MJ of electricity to cover small machinery are also supplied to assist manual construction and mortar cleaning. The logistics and transportation are modeled based on localized procurement within a 20 km radius (Table 3).

Table 3. A1 Phase Environmental Load Basic Data Calculation

Option A1	Calculation Process	Amount	**Unit**
Hydraulic lime mortar (NHL)	$142.45 \times 0.07 \times 0.03 \times 1800\,kg/m^3$	540.00	kg
	Based on 3 cm grout depth & 7% damage rate		
Tap Water	M_{mixing} (1:4) + $M_{cleaning}(2\,kg/m^2)$	220.00	kg
electricity for small machinery	$0.25\,kWh/m^2 \times 20\,m^2$	18.00 (5.0 kWh)	MJ
logistics and transportation load	$(0.54 + 0.01 + 0.22)\,t \times 20\,km$	15.40	t·km

The obtained Inventory Data was input into the openLCA software platform and mapped to the Ecoinvent 3.10 database. The characterization of data presented in Fig. 3 was derived by setting up a life cycle model.

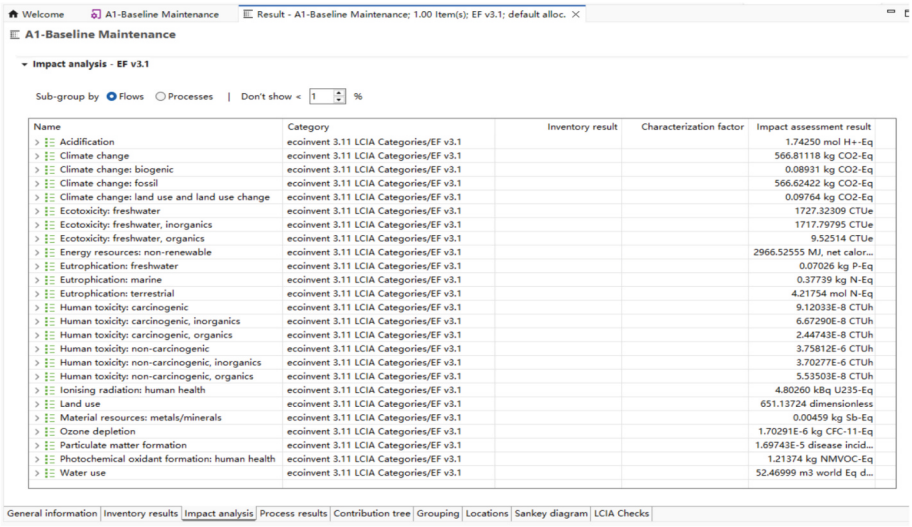

Fig. 3. The impact analysis of option A1

A2 - Traditional Retrofitting:

The basic features of option A2 involve the r structural reinforcement using reinforced concrete (RC). According to the reinforcement design requirements, this alternative will add a cumulative of 3729.60 kg of cast-in-place concrete (grade C25) and 155.40 kg of low-alloy steel reinforcement. The total mass of the added materials is estimated at 3.885 tons, representing 2.16% of the original wall's total mass. During construction, a total of 233.10 kg of tap water will be used, regarding the mixing of concrete, its curing, as well as the cleaning up of the base. One unit volume of mechanized construction (drilling and rebar installation, synthetic concrete pumping, and vibration) is estimated to consume 23.31 kWh (equivalent of 83.92 MJ) of electricity. According to the assumption of localized procurement (transport radius established at 20km), the total mass of all the concrete, rebar, and water applied in the construction is estimated, giving an alternative of 77.7 t·km of transportation turnover in the case of A2 (see Table 4).

Table 4. A2 Phase Environmental Load Basic Data Calculation

Option A2	Calculation Process	Amount	Unit
Cast-in-place concrete	1.554 m^3 × 2400 kg/m^3	3729.60	kg
Steel rebar	Reinforcement quantity corresponding to 1.554 m^3 of concrete (at 100 kg/m^3)	155.40	kg

(*continued*)

Table 4. (*continued*)

Option A2	Calculation Process	Amount	Unit
Tap water	1.554 m^3 × 150 kg/m^3	233.10	kg
	Concrete mixing (180 kg/m^3) + curing loss		
Construction power consumption	15 kWh/m^3 × 1.554 m^3 = 23.31 kWh	83.92(23.31)	MJ(kWh)
	Drilling and rebar installation/concrete vibration		
Logistics and transportation load	(3.73 + 0.16) t × 20 km	77.70	t·km

By establishing a LCA model, the final characterization results data shown in Fig. 4 were obtained.

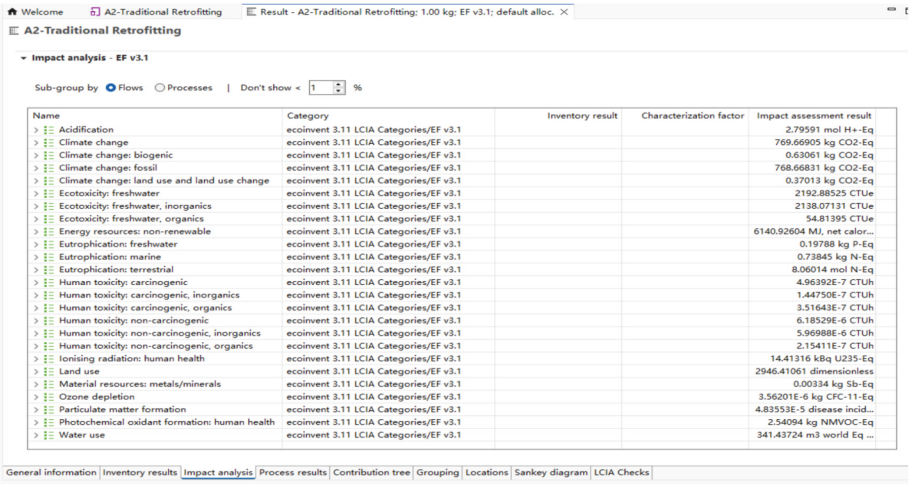

Fig. 4. The impact analysis of option A2

A3- Advanced Reinforcement (FRCM):

For Option A3, the FRCM is adopted to ensure double-sided reinforcement of the 180-ton masonry unit. Beyond enhancing structural ductility and seismic performance, this alternative creates a continuous reinforcement layer by applying fiber mesh and high-performance mortar to both interior and exterior surfaces. Accounting for double-sided window openings (25.20 m^2), the net reinforcement area (A_{net}) is 259.70 m^2. Based on a total double-sided thickness of 30 mm, 14,023.80 kg of mortar is required. The reinforcement phase utilizes alkali-resistant glass fiber mesh, requiring 142.84 kg to account for construction overlaps and a wastage coefficient of 1.1.

To support mortar mixing and substrate wetting, 2,524.28 kg of tap water is required (calculated at 18% of the mortar mass). Due to the intensive high-pressure water jet

cleaning and mechanical mixing involved in Scheme A3, construction power demand increases significantly to 311.64 kWh (equivalent to 1,121.90 MJ). Assuming localized procurement within a 20 km radius, the total transportation load—comprising mortar, fiber mesh, and construction water (approximately 16.69 tons)—is calculated at 333.60 t·km (see Table 5).

Table 5. Calculation of Environmental Inventory Data for Option A3

Option A3	Calculation	Amount	Unit
High-performance cement-based mortar	$259.70\,m^2 \times 0.03\,m \times 1800\,kg/m^3$	14023.80	kg
Alkali-resistant fiberglass mesh	$259.70 \times 2 \times 0.25\,kg/m^2 \times 1.1$	142.84	kg
Tap water	14023.80 kg × 0.18	2524.28	kg
	Calculated at 18% of the mortar mass (including mixing and wetting of the substrate)		
Construction power consumption	$1.2\ kWh/m^2 \times 259.70\,m^2 \times 3.6$	1121.90	MJ
	High-pressure water jet cleaning and mechanical agitation		
Logistics and transportation load	(14.02 + 0.14 + 2.52) t × 20km	333.60	t·km

By establishing the life cycle model, the final characterization results data shown in Fig. 5 were obtained.

4.5 Comparison of Restoration Scenarios

To evaluate the environmental performance of the different interventions, LCIA results for Scenarios A1, A2, and A3 are compared. Table 6 summarizes the key impact categories, including GWP, AP, and RU, for all three options.

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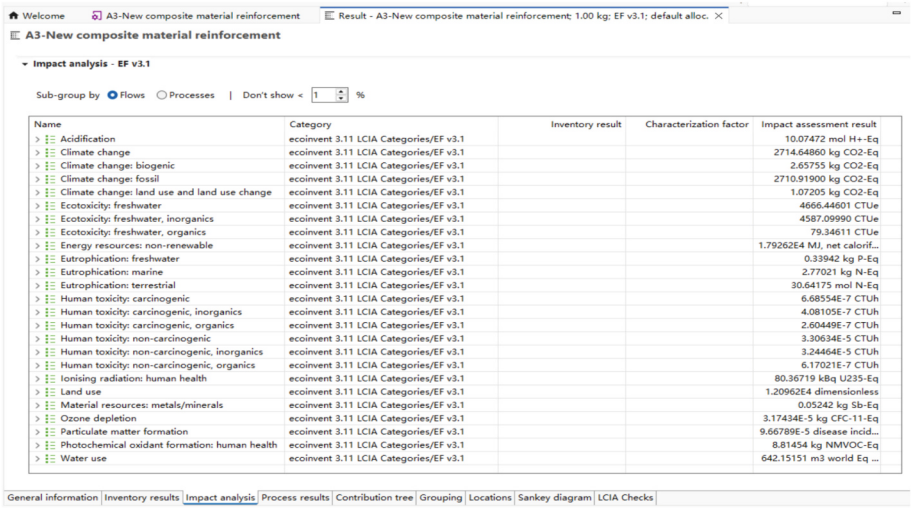

Fig. 5. The impact analysis of A3

Table 6. Summarize of LCIA results for all restoration scenarios

Impact Categories	Unit	A1: Baseline	A2: Traditional	A3: FRCM
GWP	$kgCO_2eq$	566.81	769.669	2714.649
AP	Mol H^+eq	1.743	2.796	10.075
RU	kgSbeq	4.59×10^{-3}	3.33×10^{-3}	5.242×10^{-2}

4.6 Decision Model Construction: AHP Weight Allocation and Comprehensive Evaluation

The core first step of the AHP method lies in hierarchical modeling. The systematic analysis of the natural correlation between decision-making goals and indicators of evaluation turns complex issues into a properly structured multi-level model. This model is performed top to bottom based on the following series of "objective layer-primary indicator -secondary indicator," and the structural framework in question is depicted below (see Table 7).

Table 7. AHP Hierarchical Framework

Target layer	Primary Indicators	Secondary Indicators
Selecting the optimal restoration strategy for historic church exterior walls	A. Heritage Conservation Value	A1 Reversibility

(*continued*)

Table 7. (*continued*)

Target layer	Primary Indicators	Secondary Indicators
		A2 Visual Compatibility
	B. Technical Structure Performance	B1 Enhancement Efficiency
		B2 Intervention Depth
		B3 Maturity Score
	C. Environmental Sustainability	C1 GWP (Carbon Footprint)
		C2 AP (Environmental Pollution)
		C3 Resource Use
	D. Economic Feasibility	D1Operation and Maintenance Costs
		D2 Material Lifespan

The weights of each evaluation indicator were given by the authors to provide expert judgments. The weighting process was performed by pairwise comparisons of the four primary criteria (A, B, C, and D) using Saaty's 1–9 scale. Individual judgment matrices were synthesized using the geometric mean method. This process resulted in the integrated comparison matrix for the primary indicators shown in Table 8. The values within the matrix reflect the relative importance of each criterion; for instance, the value of 1.6612 indicates that in this restoration context, Heritage Conservation Value (A) is assigned a moderate priority over Technical Structural Performance (B).

Table 8. Heritage Conservation Value - Economic Feasibility Assessment Integrated Matrix

Choosing the most sustainable strategy for restoring the exterior walls of a historic church	A Heritage Conservation Value	B Technical Structure Performance	C Environmental Sustainability	D Economic Feasibility
A. Heritage Conservation Value	1	1.6612	1.8015	2.7595
B. Technical Structure Performance	0.6020	1	1.3351	1.6438
C. Environmental Sustainability	0.5551	0.7490	1	1.2821
D. Economic Feasibility	0.3624	0.6084	0.7800	1

Table 9. The weight calculation results

Index	Weight	λmax	CI	CR
A1Reversibility	0.6025	2.0000	0.0000	0.0000 < 0.1Consistency passed
A2Visual Compatibility	0.3975			
B1Enhancement Efficiency	0.4014	3.0028	0.0014	0.0026 < 0.1Consistency check passed
B2 Intervention Depth	0.3966			
B3Maturity Score	0.2020			
C1GWP (Carbon Footprint)	0.5000	3.0007	0.0003	0.0007 < 0.1Consistency check passed
C2 AP (Environmental Pollution)	0.2012			
C3 RU	0.2987			
D1Operation and Maintenance Costs	0.4997	2.0000	0.0000	0.0000 < 0.1Consistency check passed
D2 Material Lifespan	0.5003			

Based on the calculation results of the integration matrix and weights for each indicator, the weights between the indicators at each level are summarized as follows in Tables 9 and 10.

Table 10. Summary of Weights for Selecting the Most Sustainable Historic Church Exterior Wall Restoration Strategies

Primary Indicator	Relative Weight (W_1)	Secondary Indicator	Relative Weight (W_2)	Over all Weight ($W_1 \times W_2$)
A. Heritage Conservation Value	0.3974	A1 Reversibility	0.6025	0.2394
		A2 Visual Compatibility	0.3975	0.1580
B. TechnicalStructurePerformance	0.2513	B1 Enhancement Efficiency	0.4014	0.1009
		B2 Intervention Depth	0.3966	0.0997
		B3 Maturity Score	0.2020	0.0508
C. Environmental Sustainability	0.2003	C1 GWP (Carbon Footprint)	0.5000	0.1002
		C2 AP (Environmental Pollution)	0.2012	0.0403
		C3 RU	0.2987	0.0598

(*continued*)

Table 10. (*continued*)

Primary Indicator	Relative Weight (W_1)	Secondary Indicator	Relative Weight (W_2)	Over all Weight ($W_1 \times W_2$)
D. EconomicFeasibility	0.1510	D1 Operation and Maintenance Costs	0.4997	0.0755
		D2 Material Lifespan	0.5003	0.0755

Finally, a comprehensive evaluation matrix was constructed by multiplying the overall weights of the indicators by the performance scores assigned to each restoration strategy (A1, A2, and A3). As shown in Table 11, Option A3 (FRCM) achieved the highest total score (7.5882), followed by A1 (7.0678) and A2 (6.4246).

Table 11. Comprehensive evaluation matrix for restoration strategies

Primary indicator	Secondary Indicators(comprehensive weight)	A1: Baseline	A2: Traditional	A3: Advanced
A.Heritage Conservation Value	A1 Reversibility (0.2394)	10	6	8
	A2 Visual Compatibility (0.1580)	10	9	7
B. Technical Structure Performance	B1 Enhancement Efficiency (0.1009)	1	4	9
	B2 Intervention Depth (0.0997)	10	7	6
	B3 Maturity Score (0.0508)	9	10	7
C. Environmental Sustainability	C1 GWP (0.1002)	3	5	7
	C2 AP (0.0403)	8	7	6
	C3 RU (0.0598)	9	6	8
D. Economic Feasibility	D1 O&M Costs (0.0755)	2	5	8
	D2 Material Lifespan (0.0755)	3	5	9
Total	**1.0000**	7.0678	6.4246	**7.5882**

4.7 Sensitivity Analysis

To verify the robustness of the decision-making results, a sensitivity analysis was conducted by fluctuating the weights of the primary indicators (A, B, C, and D). The results of the sensitivity analysis are illustrated in Fig. 6. The analysis demonstrates that despite

minor adjustments in the priority of environmental sustainability or economic feasibility, Option A3 consistently maintains its position as the most suitable strategy, with the exception of values of the weight of Heritage conservation larger than 0.6, where the A1 option gives better results. Nevertheless, the proposed AHP model confirms it statability in most of the cases, thus confirming the robustness of the proposed procedure (Fig. 6).

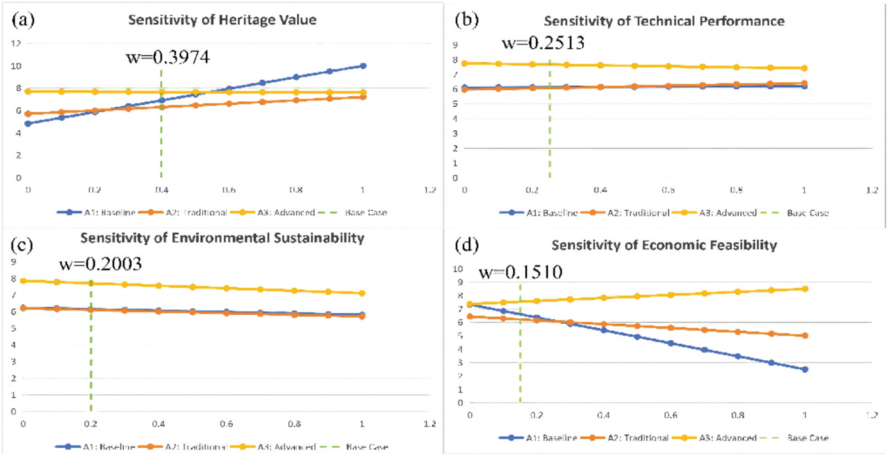

Fig. 6. Sensitivity analysis of the criteria weights for the restoration scenarios

5 Conclusion

This study constructed and validated a multi-dimensional assessment model for the restoration of historic buildings by integrating LCA and AHP. A major advantage of this model is its flexibility: it does not require HBIM model, but rather achieves quantitative analysis of the environmental performance and structural performance of restoration schemes through an integrated CAD-LCA-AHP approach, even with limited basic data. The case study of the Lady Mary of the Belt Church demonstrates that the FRCM reinforcement scheme significantly reduces GWP and AP while meeting structural safety and heritage preservation values, confirming it as the optimal strategy for green restoration of historic buildings. Sensitivity analysis was introduced to quantify the impact of fluctuations in expert weights on the results. The analysis shows that within the current expert consensus weights (e.g., heritage value $w = 0.3974$) and their significant fluctuation range, the scheme ranking remains highly robust. This significant safety margin strongly demonstrates the high reliability and application value of this assessment framework in addressing the uncertainty of subjective decision-making.

While this study confirms the potential of the CAD-LCA-AHP approach in the quantitative analysis of environmental performance, certain limitations remain. Current research focuses on a representative 12.95-m-long wall section and has not yet fully simulated the extreme changes in complex geometries such as the church dome and apse. Furthermore, due to the limited coverage of existing Environmental Declaration (EPD) databases for heritage conservation materials, evaluation indicators do not yet

encompass eutrophication and human toxicity. Future research will aim to expand the evaluation boundaries, utilize a more comprehensive background database to broaden evaluation dimensions, and validate the applicability of the framework across all spatial dimensions. Simultaneously, the research will explore integrating real-time monitoring data into deeper digital models to achieve dynamic sensitivity analysis, aiming to provide more universal and intelligent decision support for the sustainable restoration of cultural heritage under complex constraints.

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