Supporting Sustainable Interventions in the Historical Center of Lugoj City, Romania, Through Life-Cycle Assessment Framework

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Abstract. This study aims to integrate Life-Cycle Assessment into the heritage conservation framework for Lugoj's historical center. Typological strategies compare minimal repairs to retrofits for masonry structures, prioritizing life extensions and low-impact interventions. The results favor low-impact interventions that extend service life.

Keywords: Life-cycle Assessment, Restoration, Sustainable Intervention, LCA Framework, Heritage Preservation.

1 Introduction

Lugoj is a city in Timiș County, Romania, located along the Timiș River. It has an architectural heritage that reflects its multicultural history. In the 19th and early 20th centuries, Lugoj was under Austro-Hungarian influence and evolved into an urban center defined by eclectic, neoclassical, Art Nouveau, and Secession styles.
Lugoj's built environment is dominated by eclectic architecture blending neoclassical elements with Art Nouveau influences. The most distinctive are the Secession buildings, which keep structural elements visible and use simple geometric patterns, fine lines, and modest decoration to combine functionality with aesthetics.
Among the landmarks are The Iron Bridge, the Electric Watch, Bejan Palace, Haberehn Palace, Hotel Dacia, Peta-Puscariu House, Vertes Palace, Old Theatre, and many others (Bureșin, 2022).

The Iron Bridge, built in 1902, replaced an old wooden structure, connecting the historically divided 'Romanian Lugoj' and 'German Lugoj' and serving as a customs point between the two towns. Along with the construction of the Iron Bridge, two buildings, Bejan Palace and Haberehn Palace, were built on the Romanian side, flanking it (Municipality of Lugoj, 2026).

The Bejan Palace was built following the Viennese 'rental palace' model. Its main façade faces Unirii Street, characterized by windows framed with pediments bearing

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allegorical figures above. It features a steeply pitched mansard roof adorned with circular openings and rich decorations.

The Haberehn Palace was built in 1879 and is situated opposite the Bejan Palace, thus marking the beginning of Unirii Street. The building features an eclectic style, with numerous façade ornaments, dormer windows, and wrought iron balconies (Municipality of Lugoj, 2026).

Fig. 1. Left: Bejan Palace, right: Haberehn Palace, and centre: The Iron Bridge.

The Old Prefecture is among the largest administrative buildings in the city, located on the Romanian side, and was built between 1843 and 1859. This neoclassical structure has an impressive façade with Gothic influences, featuring windows framed by sturdy Ionic columns embedded in the walls, and a simple yet balanced central fronton.

Fig. 2. Old Prefecture building.

In the German Lugoj, equally emblematic, stands the Vertes Palace, a secession-style building located near the Iron Bridge. Opposite it, Peta-Puscariu House, now an art gallery, stands out for its neoclassical simplicity. Like other buildings, it has a balcony on the chamfered corner, with extremities framed by semicircular pediments.

Right in front of the chamfered corner, the Electric Watch was placed in 1924, a gift from the city's watchmaker, showcasing a modern metal frame on a sturdy base with illuminated rectangular dials (Bureșin, 2022).

Fig. 3. Peta-Puscariu House (now Pro Arte Gallery) and the Electric Watch.

Right in the city's old center stands Dacia Hotel, originally functioning as an inn, which has become a social center for balls and city events. The building has undergone some changes over its lifetime, but currently retains its original eclectic-neogothic form. A 1931 fire destroyed the statues atop its massive octagonal pilasters, losing its ‘doll-house’ resemblance. The building was restored in 2002 to evoke old postcards and retain partial functions, but lost its grand restaurant, symbolizing both resilience and difficulties of maintaining historic hospitality venues (Bureșin 2022).

Fig. 4. Dacia Hotel.

The major historical buildings in the old city center feature neoclassical architecture with characteristic elements such as chamfered corners, corner balconies, and bay windows. The most striking visual characteristic in Lugoj’s architecture is the geometric Secession style, which reimagines classical ideas with layered, refined lines on its facades. However, these buildings are deteriorating due to multiple factors, mainly a lack of maintenance, inappropriate interventions, and material incompatibility.

Recent studies have emphasized the role of digital documentation, heritage analysis, and preservation-oriented decision-making in supporting cultural heritage management, which is consistent with the present study's focus on life-cycle-based conservation planning (Neikova, 2024).

Within this context, the present study contributes by extending Life-Cycle Assessment to the conservation of the historic center of Lugoj, showing how environmental evaluation can support heritage-oriented intervention planning. By combining typological analysis with LCA logic, the paper aligns conservation priorities with both preservation values and long-term sustainability objectives (Peteva, 2024).

2 Life-cycle Assessment in the Heritage Preservation Process

The concept of life-cycle assessment (LCA) is largely used in the building sector for assessment of the environmental impacts of the construction activities, materials, maintenance, and demolition. In the field of heritage preservation, LCA represents a useful tool to assess the impact of the proposed intervention measures, putting in balance principles like authenticity, compatibility, reversibility, and long-term durability. It is not a conservation principle, but rather an assessment tool, able to clarify which kind of intervention will necessitate more frequent maintenance, such as low-carbon repair mortars, or whether a consolidation procedure could lead to reduced operational energy but generate environmental impact that cannot be compensated in a realistic service life.

One concept that is becoming more widely used in the field of heritage preservation is the concept of the `green heritage science`, where the focus is on the responsibility that comes with conservation practice. From the material research that is made in the laboratory to the intervention planning and management strategy development, each decision comes with an environmental impact that must be assessed (Elnaggar, 2024). Moreover, considering a proper reference study period in the process of designing the intervention process, as well as understanding the maintenance and replacement of elements together with repair cycles, are particularly relevant in conservation science (Fahlstedt et al., 2024).

2.1 The Role of the LCA Framework in the Heritage Preservation Workflow

The process of heritage preservation is complex, and environmental considerations have a big impact on several phases of the project, such as diagnosis, definition of the intervention objective, selection of materials, planning, and management plan thinking. At each stage of the process, LCA can be integrated to ensure more durable solutions:

- Concept stage – quick assessment of several alternative solutions, for example, repair work instead of invasive consolidations; the aim is to ensure the necessity or compatibility of each proposed solution and to avoid unnecessarily invasive interventions.

- Design stage – selection of proper materials and techniques and understanding of the expected service-life for each solution; the aim is to understand the implications of each design decision, even the environmental effects of production and transportation of selected materials.
- Maintenance stage – thinking the repair cycles, such as surface treatments, repainting, repair works, replacement of degraded elements and their environmental implications; the aim is to limit the life-cycle impacts and to ensure as much as possible a preventive conservation practice, because the life service of a heritage building can be much longer than that of a contemporary building.

In the workflow of the heritage preservation process, LCA represents a tool for supporting decisions, allowing the involved decision-makers to understand that interventions on historical buildings should be seen as a life strategy rather than only quick upgrades (Angrisano et al., 2021).

2.2 The Requirements in Heritage-specific Interventions: Compatibility, Durability, and Uncertainty

The process of heritage preservation comes with specific constraints that influence the LCA interpretation, such as material compatibility and hygrothermal safety, durability and service-life extensions, and data gaps and uncertainty.

The traditional materials that are used in historical buildings, such as burnt clay brick with lime-based mortars, can be sensitive to environmental stress, such as moisture, freeze-thaw cycles, and acid rains. From the point of view of the LCA framework, militating for a technically \`low impact\` proposal is not sustainable if it means that the building will require frequent repairs and if the process of decay will be accelerated. That is the reason why, in the light of the LCA framework, it is better to select materials that, despite being more innovative and maybe more expensive, present the ability to extend the service life and maintenance demand of the building. The material performance should be assessed not only by the initial environmental impact, but also by the durability and context-specific sustainability in the use stage (Mazzetto, 2025).

A specific particularity of the heritage buildings is their capacity to remain in service for very long periods, usually much longer than many contemporary buildings. So, insisting on service-life extensions rather than replacing represents an important aspect of LCA, which depends a lot on what lifetime expectancy is used (Fahlstedt et al., 2024).

But when it comes to heritage buildings, there is a challenge in understanding the building, because usually, full documentation is lacking, especially about past interventions or details regarding traditional materials that were used. In this case, LCA relies on a combination of data generated by literature review, database access, survey, historical documentation research, and in-situ tests. Within the \`green heritage science\` perspective, LCA framework can help to overcome uncertainty and guide decisions (Elnaggar, 2024).

2.3 Methodology and LCA Assumptions

The proposed framework's applicability can be established through a simplified Life-Cycle Assessment model following ISO 14040 principles. Although the collection of data from the actual case study buildings in Lugoj wasn't finished yet, based on the collected data and explored data from similar case studies analysis, a probable scenario was defined, with the aim of comparing the environmental impact of different intervention strategies applicable to masonry heritage buildings in Lugoj. The functional unit is considered to be 1 square meter of façade over a 50-year reference study period. The system boundaries include the production of material, its transport and application, but also the maintenance stages. The environmental indicator that was selected is the Global Warming Potential, widely used in building LCA to evaluate the maintenance-related emissions in early-stages assessments, through a simplified calculation presented in Equation 1 (Zhang et al., 2024).

$$GWPtota\ l= \sum(mi \times EFi) + \sum(nj \times GWPmaintenance,j) \qquad (1)$$

Where m_i represents the material quantity (kg/m^2), Ef_i represents the emission factor (kg CO_2/kg), n_j represents the number of maintenance cycles and $GWP_{maintenance,j}$ represents the impact per maintenance intervention.

This approach is aligned with the methods for assessing the emission-factor-based LCA that are widely used in building evaluation studies (Huang et al., 2024).

2.4 LCA Framework and Lugoj City Center

The historical center of Lugoj city represents a combination of architectural value and contemporary functional needs (Draghici & Onescu, 2025). The main challenge identified in the central area of the city is represented by the lack of connection between the historical identity of the city and modern community needs, highlighting the importance of coherent strategies for the valorization of the heritage buildings and historical public space (Draghici et al., 2025). In this case, the LCA framework matters even more because the interventions have several impacts on buildings and public space, and long-term capacity would influence the decisions that cannot be imagined as isolated.

A LCA framework adapted for the city of Lugoj should focus on typical intervention families rather than on each building, to ensure a more sustainable preservation process. For example, several building typologies could be considered, such as load-bearing masonry buildings with historical mortars, mixed masonry-timber structures (at the level of floors, roofs), or buildings with already existing retrofitting elements, for an easier vulnerability assessment (Azap et al., 2018). Each typology comes with different needs in terms of intervention, repair needs, moisture problems etc. Establishing typological classes would allow the LCA framework to be used as a planning tool, by comparing `quick repair` strategies with `extensive retrofit` strategies' impact. Moreover, it would allow the definition of specific areas where more extensive measures could ensure a better life-cycle outcome, such as the insulation of the roof, for example, in areas where the aesthetic impact is not negative.

So, a set of recommendations for the interventions in the city center of Lugoj, in the context of the LCA framework, can be defined:

- Maximizing the impact of minimal interventions – despite the trend to prefer repair work, which is seen as an environmentally friendly strategy, in the light of the LCA, there should also be considered the impact of repeated repair work to support such minimal intervention. By considering the decay risk and replacement cycles for the heritage building in Lugoj, the LCA can help assess whether maintaining historical materials, even if they are replaced more often, is better in the long term than proposing more modern solutions that come with higher costs and specific application procedures.
- Considering the operational energy under conservation constraints - in most cases, heritage buildings have a high operational energy demand because of a lack of insulation, yet extensive energy retrofit strategies are not allowed due to historical constraints. LCA allows the comparison of different levels of retrofit strategies to ensure compatibility with the historical substrates and includes the impact of maintenance (Angrisano et al.).
- Considering innovative materials under compatibility rules – LCA can help assess the real advantages of innovative materials, rather than looking only at the performance claims alone. In many cases, materials that were designed for the application on heritage buildings have shown increased carbon footprint and operational energy impacts (Rubio-Aguinaga et al., 2025), highlighting the importance of investigating the opportunities of sustainable eco-materials (Mosiu et al., 2025).
- Prioritizing interventions across multiple aspects – the selection of the best materials, techniques, and strategies can be scaled from one element of a building to an entire historical area of a city, allowing authorities to prioritize which measures deliver the best life-cycle benefits.

For the heritage preservation framework in Lugoj city, LCA represents an assessment tool that comes to help the conservation principles. It helps identify and select the intervention strategies that are not only compatible with the original substrates and durable but also have a low environmental impact. As a future research direction, this topic could provide a bridge between Lugoj's heritage values and typologies and a clear comparison of intervention options.

To demonstrate the applicability of the framework, two typical intervention scenarios for masonry facades were considered (Table 1), as follows:

(i) Scenario A, for minimal repair strategy: lime-based mortar repair, repainting every 10 years, with no improvements in operational energy

(ii) Scenario B, for moderate retrofit strategy: repair and insulating lime plaster layer, with repainting every 20 years, and approximately 15-20% reduction in operational energy demand.

Table 1. Comparative simplified Life-Cycle Assessment (LCA) results for two intervention strategies applied to historical masonry façades, expressed per functional unit (1 m² over a 50-year reference study period).

Parameter	Scenario A (Minimal repair)	Scenario B (Moderate retrofit)
Initial embodied carbon (kg CO_2/m^2)	12	38
Maintenance cycle	10 years	20 years
Number of cycles (50 yrs)	5	2
Maintenance impact per cycle (kg CO_2/m^2)	8	10
Total maintenance impact	40	20
Operational energy reduction	0%	18%
Total GWP (50 yrs)	52 kg CO_2/m^2	58 kg CO_2/m^2 (without energy savings)
Adjusted GWP (with energy savings)	52	~45–50
Initial embodied carbon (kg CO_2/m^2)	12	38

The values considered are based on the investigation of literature review ranges for the repair and retrofit intervention of masonry facades (Wise et al., 2023)

The results highlight the initial higher embodied impact of the second scenario (scenario B), balanced by the reduced maintenance frequency and operational energy demands. So, on a total life-cycle emissions assessment, the second scenario is comparable or even better than the first one, confirming that in heritage contexts, the minimal intervention approach is not always the one with the lowest impact when long-term performance is considered.

3 Conclusion

Integrating Life-Cycle Assessment (LCA) into the heritage preservation process offers a structured way to understand the long-term environmental impacts of conservation strategies. The preservation process is enhanced by LCA, which evaluates trade-offs between authenticity, material compatibility, reversibility, and long-term durability. In green heritage science, LCA aids informed decision-making by helping choose materials, intervention strategies, and maintenance plans that balance environmental sustainability with cultural preservation.

Adapting the LCA framework for Lugoj's city center to local typologies demonstrates the method's ability to act as both a diagnostic and strategic tool. It allows comparing families of interventions—from minimal repairs to extensive retrofits—based on service-life extension, operational energy demand, and embodied impact. This assessment is based on simplified assumptions and data derived from a literature review, caused by a lack of detailed local inventories or databases. Data gaps represent a common limitation in heritage LCA applications, requiring sometimes parametric approaches. Future work should include in-situ measurements, investigation of local projects databases and dynamic LCA modelling to improve accuracy. The demonstrative LCA comparison clearly shows that strategies that involve moderate retrofit interventions can reduce the life-cycle emissions with approximately 5-15%, when the maintenance and operational energy costs are considered together, highlighting the importance of integrating quantitative LCA into early decision-making processes for heritage conservation and preservation work.

Using LCA in heritage preservation still faces difficulties due to data uncertainties, service-life assumptions, and the compatibility of traditional materials with modern ones. Addressing these issues through interdisciplinary research and localized databases would strengthen the method's reliability and transferability. Ultimately, integrating LCA into heritage management frameworks encourages a proactive conservation approach—one that views each intervention not as an isolated act of repair but as part of a broader life strategy to preserve the built heritage and its environmental legacy.

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