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Development of a Heritage Life Cycle Assessment (H-LCA) framework: Integrating sustainability metrics and cultural preservation in heritage buildings

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ABSTRACT

This study explores the integration of sustainability in heritage buildings, focusing on the unique challenges posed by traditional construction methods and materials. Using eight heritage buildings from Strovolos, Cyprus, as case studies, the research evaluates their environmental performance through a tailored Life Cycle Assessment (LCA). These buildings, spanning from the Ottoman era to the mid-20th century, represent diverse architectural styles and traditional materials, such as adobe, stone, and lime plaster. The methodology encompasses three components: the development of a Life Cycle Inventory (LCI) for primary materials, a gap analysis of the European Commission's Level(s) framework, and proposals for adapting the framework to heritage-specific needs. The LCI evaluates cradle-to-gate processes, revealing the minimal environmental impact of non-industrialized, traditional methods. However, the absence of standardized indicators for heritage materials highlights the limitations of conventional LCA approaches. Initial findings underscore the inherent sustainability of traditional materials due to their local sourcing and low embodied energy. The gap analysis identifies deficiencies in the Level(s) framework for assessing heritage buildings, such as the lack of indicators for cultural value and restoration energy impacts. Proposed adaptations include new metrics addressing these gaps, offering a comprehensive approach to balancing sustainability with heritage preservation.

1. Introduction

Heritage building materials are inherently sustainable, as their construction predates industrialized processes, relying instead on locally sourced, natural materials. However, this poses a critical challenge for modern sustainability assessments. The Life Cycle Assessment (LCA) indicators of these materials unavoidably register as zero, due to the lack of quantifiable data on their environmental impact during production and use. This absence of measurable benchmarks makes it difficult to evaluate their true environmental footprint or to compare them against contemporary materials. Consequently, traditional LCA methodologies, designed for industrialized processes, are inadequate for assessing heritage buildings, leaving a significant gap in our understanding of their sustainability performance.

Unlike modern constructions, heritage buildings were not designed with environmental performance in mind. Many were built using traditional techniques and locally sourced materials, which are inherently more sustainable compared to industrialized materials (Xystouris et al., 2021). However, the lack of modern energy efficiency measures, often results in high energy consumption during their use phase (Lidelöw et al., 2019). Additionally, retrofitting these buildings to meet current sustainability standards without compromising their cultural and historical value presents a unique set of challenges. Consequently, there is a growing need for a tailored approach to assess and enhance the environmental performance of heritage buildings, one that respects their historical character while addressing contemporary sustainability concerns (Nair et al., 2022).

Traditional construction methods and materials are integral to the identity of heritage buildings but also complicate sustainability assessments. Materials such as stone, wood, and lime plaster were typically sourced and crafted locally, resulting in minimal embodied energy during their original construction (Zhao et al., 2019). However, their environmental impact is difficult to quantify due to the lack of standardized data and the uniqueness of traditional practices. Moreover, modern LCA methodologies, which are well-established for contemporary materials, often fall short when applied to traditional materials and

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heritage buildings (Mazzetto, 2024). These methodologies typically assume industrialized processes and standardized data, making them ill-suited to capture the nuances of traditional construction. The absence of clear benchmarks for traditional materials, coupled with the difficulty of balancing preservation and sustainability goals, underscores the need for a specialized framework to evaluate the environmental performance of heritage buildings (Munarim and Ghisi, 2016).

In order to address sustainability concerns in the built environment in a unified and comprehensive manner, the European Commission developed the **Level(s)** framework (Klumbyte et al., 2023). This voluntary scheme provides a structured approach to assessing and reporting on the environmental performance of buildings across their life cycle, focusing on aspects such as energy efficiency, resource use, and indoor environmental quality. By aligning construction and renovation practices with sustainability goals, Level(s) aims to advance the transition toward a more sustainable and resilient built environment (Spudys et al., 2024).

The main research questions addressed by this study are:

1. How can the sustainability performance of heritage buildings be analyzed using Life Cycle Assessment (LCA), considering the unique characteristics of traditional materials and construction methods?
2. What are the specific limitations of applying the European Commission's Level(s) framework to heritage buildings, particularly concerning traditional materials, restoration processes, and socio-cultural values?
3. What enhancements or additional indicators can be proposed to the Level(s) framework to make it more applicable for the comprehensive assessment of heritage buildings' sustainability performance?

To address these challenges, this study analyzes the sustainability performance of heritage buildings in terms of LCA, focusing on the environmental impact of traditional construction materials and methods. To exemplify this, eight heritage buildings constructed during the 19th and early 20th centuries in Strovolos, Cyprus, were selected for analysis. These case studies represent a diverse range of traditional materials and construction techniques. The sustainability performance of these materials was evaluated through the development of a Life Cycle Inventory (LCI), focusing on the cradle-to-gate manufacturing processes for the primary materials used. This approach provides insights into the environmental performance of heritage materials while acknowledging the limitations of traditional LCA methods for such contexts. A comprehensive gap assessment was conducted to identify limitations in the existing Level(s) framework concerning its application to heritage buildings. Recognizing these gaps, the study explores potential enhancements to the framework that would allow it to better address the unique requirements of heritage buildings. These proposed additions aim to capture both the environmental and cultural dimensions of heritage preservation, acknowledging the intricate balance between sustainability goals and the conservation of historical authenticity.

2. 2. Methodology

This section outlines the methodological framework developed to assess the sustainability performance of heritage buildings. It includes three main components: the selection of eight heritage buildings in Cyprus as case studies, the development of their LCI to evaluate the environmental impact of traditional materials, and a gap analysis of the European Commission's **Level(s)** framework. The selected buildings represent diverse architectural styles and traditional materials, ensuring a comprehensive evaluation. The LCI process maps the materials and their cradle-to-gate manufacturing processes, adapting standard practices to heritage contexts. Finally, the Level(s) gap analysis identifies missing indicators for heritage-specific aspects, and proposals are made to enhance the framework for assessing both environmental and cultural dimensions of heritage buildings.

The methodology is divided into the following key components:

1. **Building Selection:** The rationale for selecting the eight heritage buildings and their descriptions are presented in 3.
2. **LCI Development:** The process of developing the LCI for the selected buildings and the challenges of evaluating traditional materials are discussed in 4.
3. **Level(s) gap assessment and enhancement proposals:** A gap analysis of the European Commission's **Level(s)** framework for heritage buildings, identifying missing indicators for traditional material sustainability, restoration energy impacts, and socio-cultural values, and targeted enhancements to address these limitations.

2.1. *Selection of the eight heritage buildings*

The study began with the selection of eight heritage buildings in Cyprus. These buildings were chosen based on specific criteria to ensure a comprehensive and representative analysis of the country's heritage building stock. The rationale and detailed description of the selection process are presented in 3. This selection ensures that the framework is applicable to diverse heritage building types and materials, providing a strong foundation for the study.

2.2. *Life Cycle Inventory (LCI) of building materials*

Following the selection of the buildings, their Life Cycle Inventory (LCI) was developed. This involved mapping the materials used in their construction and analyzing their environmental impact. The primary materials, including traditional ones such as limestone, timber, and mudbricks, were studied in detail. The LCI analysis revealed a key limitation: traditional materials, having no industrialized production processes, lack measurable environmental impact indicators. This finding is discussed in 4, highlighting the inadequacy of traditional LCA methodologies when applied to heritage materials.

The study further examined the production processes of the primary materials used in the selected heritage buildings. This analysis was conducted in accordance with standard LCA practices but adapted to accommodate the unique characteristics of traditional materials. Processes such as the extraction, preparation, and application of materials like mudbricks, lime plaster, and gypsum were documented to provide insights into their environmental performance. This step also laid the groundwork for the development of a tailored sustainability assessment methodology for heritage buildings.

2.3. *Gap Analysis and Proposals for Level(s) Framework Adaptation*

A gap analysis of the European Commission's **Level(s)** framework was conducted to evaluate its suitability for assessing the sustainability of heritage buildings. This process involved identifying limitations in the framework, particularly regarding its ability to account for traditional material sustainability, the embodied energy of restoration activities, and the socio-cultural dimensions of heritage conservation. Based on this analysis, the study developed proposals for additional indicators to adapt the framework for heritage-specific applications, addressing the unique environmental and cultural aspects of these buildings.

3. Overview of architectural and structural features of the selected heritage buildings

The selection of eight heritage buildings from the Strovolos municipality in Nicosia, Cyprus, was conducted to ensure a representative analysis of the region's architectural heritage. These buildings were chosen based on criteria that emphasize architectural diversity, historical significance, material variety, and conservation status. The selection process aimed to cover a range of construction periods, styles, and materials to deliver insights applicable to a broad spectrum of heritage buildings. Information concerning the selected buildings, including their general parcel and structural characteristics, is provided in (Fokaides, 2024).

The selected heritage buildings are located in the Chryseleousa quarter of the Strovolos municipality, within the Nicosia district. These parcels reflect the diverse urban and suburban characteristics of the area. Parcel sizes range from a compact 47 m^2 (S6), representing a functional structure, to a spacious 1022 m^2 (S4), showcasing a historically significant property. The buildings are distributed along prominent streets with historical and urban value.

- The detailed information for the eight selected heritage buildings, including parcel characteristics, structural details, and material compositions, is available in an open dataset (Fokaides, 2024). The dataset includes detailed architectural and structural characteristics of the eight selected heritage buildings, offering insights into their historical, architectural, and sustainability value.
- The construction dates span nearly a century, reflecting shifts in design and material use across different historical periods. The oldest building, S7, was constructed in 1864 during the Ottoman period, providing a glimpse into the craftsmanship and construction practices of that era. Early 20th-century examples, such as S1, S2, and S4, represent the urban residential styles of the time, blending functionality with traditional design. In contrast, S3, built in 1953, reflects mid-20th-century trends, incorporating more modern approaches to construction while retaining elements of traditional techniques.
- The buildings' primary construction materials include adobe stone and stone, both integral to the heritage of the region. Adobe stone, widely used in S1, S2, S3, S4, S7, and S8, demonstrates the material's versatility and sustainability, as it was locally sourced and adapted to both urban and rural settings. On the other hand, stone, featured prominently in S5 and S6, highlights its durability and suitability for specific environmental and functional needs. These stone-built structures were often designed for rural or specialized purposes. The presence of these materials across the dataset enables a comprehensive evaluation of their environmental sustainability and the challenges associated with their preservation.

The dataset further categorizes the buildings based on their architectural class and current condition. Buildings such as S1, S2, S5, and S6 are classified as Class B, indicating significant architectural and historical value. In contrast, S4 is categorized as Class D, representing a more modest design yet retaining specific historical importance due to its age and typology Fig. 1.

- The conditions of the buildings vary, with most, including S1, S2, and S5 through S8, being in good condition and requiring minimal restoration. S3 is in fair condition, exhibiting visible cracks, while S4 is in poor condition, reflecting advanced degradation and an urgent need for preservation.
- The structural characteristics of the buildings provide additional insights into their design and functionality. The enclosed extents of the buildings range from compact layouts to expansive structures, reflecting their intended use and architectural significance. S6, with an enclosed area of 58 square meters, likely served as a compact, functional structure, designed for simplicity and efficiency. In contrast, S4, with an enclosed area of 222 square meters, represents a more spacious layout, typical of prominent heritage properties with greater historical or cultural significance.
- The number of floors further emphasizes the variety in architectural forms. Single-story buildings, such as S5 and S6, are associated with simpler designs, often serving functional or rural purposes. Multi-story structures, including S2, S4, S7, and S8, reflect more complex architectural expressions, often tied to urban residential or public uses.
- The diversity among the selected buildings ensures a comprehensive representation of Nicosia's architectural heritage. S1 and S2 illustrate early 20th-century urban residences, built with adobe stone and reflecting typical residential styles of the period. S3 and S4 offer examples of transitional architectural approaches, with S3 showcasing mid-20th-century trends and S4 embodying the late Ottoman-era design. S5 and S6, smaller stone-built structures, highlight the adaptability of stone for functional or rural applications. Finally, S7 and S8, the oldest buildings in the dataset, demonstrate the longevity of adobe stone and provide valuable insights into Ottoman-era construction techniques.

The diversity in architectural styles, materials, and conditions among these eight buildings provides an ideal foundation for testing the H-LCA framework. By including a variety of structures, the study ensures the framework is adaptable to different heritage contexts.

4. Heritage building materials Life Cycle Inventory (LCI)

The environmental analysis of the selected heritage buildings incorporates a cradle-to-gate assessment of the primary materials used in their construction. This approach evaluates the environmental impact from raw material extraction to the manufacturing stage, excluding the use and end-of-life phases. The materials analyzed include stone, clay soil, timber, lime plaster, gypsum plaster, and paint, each integral to the architectural heritage of the sample. A cradle-to-gate assessment is employed because detailed information regarding the operational lifespan and end-of-life scenarios of the buildings is unavailable (Artopoulos et al., 2024). This limitation is common in heritage structures, where historical records often lack such data. For each material, the analysis includes flow charts of the production process, a short description, and tabulated information detailing key manufacturing characteristics and environmental parameters Table 1.

4.1. Stone

Stone was primarily used in the construction of load-bearing walls and structural foundations, evident in buildings such as S5 and S6. The material provided durability and strength, essential for the longevity of these structures. Its thermal mass helped regulate indoor temperatures, making it suitable for both functional and residential buildings (Jiménez de Madariaga, 2021).

Fig. 2 illustrates the cradle-to-gate production process for limestone, focusing on its manufacturing phase and highlighting the reliance on manual and human labor. This process, fundamental to the use of limestone in heritage construction, is depicted in five distinct stages within defined system boundaries. The process begins with **mineral collection and extraction**, where raw limestone is manually collected from natural deposits, reflecting traditional labor-intensive practices. The extracted limestone undergoes **crushing**, performed by human labor, which reduces the material to manageable sizes. This is followed by **milling**, where the crushed limestone is ground into finer particles to meet construction specifications. At this stage, a standard unit weight of 1 kg is processed. Once prepared, the limestone is subjected to **transportation of raw materials**, a stage that employs traditional methods using animals to deliver the material to construction sites. This step minimizes the environmental impact and generates negligible waste, typically less than 1 kg. Finally, the material is applied on-site during the built-up structural limestone phase, where it is used to construct

Fig. 1. Example of information and drawings for a heritage building analyzed (Fokaides, 2024).

Table 1
General Parcel and Structural Characteristics of the Selected Heritage Buildings.

A. GENERAL PARCEL INFORMATION

	S1	S2	S3	S4	S5	S6	S7	S8
DISTRICT	Nicosia	Nicosia	Nicosia	Nicosia	Nicosia	Nicosia	Nicosia	Nicosia
MUNICIPALITY / COMMUNITY	Dimos Strovolou	Dimos Strovolou	Dimos Strovolou	Dimos Strovolou	Dimos Strovolou	Dimos Strovolou	Dimos Strovolou	Dimos Strovolou
ADDRESS	Archiepiskopou Kyprianou 81	Makedonnitissis Kyprianou	Makedonnitissis 5	Iras 1 - 3	Kyprianou 79	Kyprianou 77	Kyprianou 75	Kyprianou 73
QUARTER	Chryseleousa	Chryseleousa	Chryseleousa	Chryseleousa	Chryseleousa	Chryseleousa	Chryseleousa	Chryseleousa
BLOCK/REGISTRA TION NUMBER	2/256	2/578	2/221	2/479	2/112	2/113	2/114	2/559
SHEET/PLAN	21/1012V04	21/1012V04	21/1012V04	21/1012V04	21/1012V04	21/1012V04	21/1012V04	21/1012V04
PARCEL AREA (m²)	707	284	-	1022	84	47	270	321
PARCEL NUMBER	230	456	192	224	107	108	109	439

B. PARCEL CHARACTERISTICS

	S1	S2	S3	S4	S5	S6	S7	S8
UNIT YEAR BUILT	1910	1925	1953	1908	1916	1916	1864	-
UNIT FRAME TYPE	Adobe Stone	Adobe Stone	Adobe Stone	Adobe Stone	Stone	Stone	Adobe Stone	Adobe Stone
UNIT CLASS	B	B	B	D	B	B	C	C
UNIT CONDITION	Good	Good	Fair Good	Poor	Good	Good	Good	Good
UNIT DISABILITY	None	None	Cracks	Cracks	None	None	None	None
UNIT ENCLOSED EXTENT	219	107	121	222	75	58	221	
UNIT OUTBUILDING EXTENT	95	18	-	-	-	-	-	-
UNIT FLOOR TOTAL NUMBER	1	2	1	2	1	1	2	2

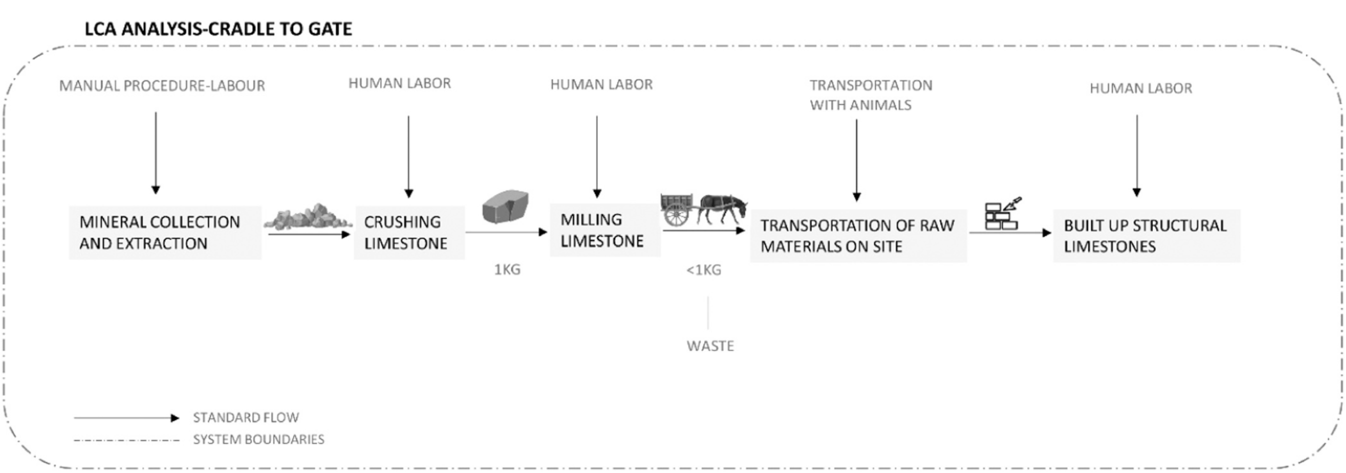

Fig. 2. Cradle-to-gate analysis of stone.

structural components under **human labor**.

Table 2 presents the cradle-to-gate production process for stone, including a short description of the production stages, their key features as well as the input and output stages.

4.2. Clay Soil

Clay soil was a key material, particularly for adobe stone construction in S1, S2, S3, S4, S7, and S8. It was molded into blocks and used for

Table 2
Cradle-to-gate production process for limestone.

Stage	Description	Inputs	Outputs	Key Features
Mineral Collection and Extraction	Manual collection of limestone from natural deposits.	Manual labor	Raw limestone	Labor-intensive, traditional methods.
Crushing Limestone	Crushing raw limestone into smaller fragments.	Human labor	Crushed limestone	Reduces material size for processing.
Milling Limestone	Milling crushed limestone into finer particles to achieve standard specifications.	Human labor, 1 kg limestone	Milled limestone (1 kg)	Standardizes material weight.
Transportation of Raw Materials	Transporting limestone to construction sites using animals.	Animal labor	Milled limestone (<1 kg waste)	Low environmental impact transportation.
Built-Up Structural Limestone	On-site assembly and construction using limestone for structural purposes.	Human labor	Constructed components	Final application phase.

walls, leveraging its natural insulation properties to maintain comfortable indoor environments. The local availability of clay soil made it a sustainable choice for these early 20th-century urban and semi-rural residences (Christoforou et al., 2016).

In Fig. 3 the cradle-to-gate process for clay soil production is illustrated, focusing on its manufacturing phase and emphasizing the reliance on traditional methods and human labor. This process, integral to the use of clay soil in heritage construction, is depicted in five distinct stages within defined system boundaries.

The process begins with **mineral collection and extraction**, where raw clay soil is manually collected from natural deposits, reflecting traditional, labor-intensive techniques. The collected clay soil, with a standard unit weight of 1 kg, is then subjected to **transportation of raw materials**, where animals are used to deliver the material to construction sites. This stage employs environmentally low-impact methods, ensuring minimal waste generation. Once delivered, the clay soil undergoes **mixing on-site**, where human labor combines the raw material with water to achieve the desired consistency for construction purposes. This step ensures that the clay soil is prepared for its final application. The process concludes with the **built-up clay mud phase**, where human labor is used to assemble and apply the material on-site to construct structural components.

Table 3 presents the cradle-to-gate production process for clay soil, including a short description of the production stages, their key features as well as the input and output stages.

4.3. *Timber*

Timber was extensively used for structural elements such as roof beams, flooring, and door and window frames. Its adaptability is seen in decorative features and functional uses, such as the multi-story configurations of S2, S4, S7, and S8. The lightweight and renewable nature of timber made it a practical choice for these heritage structures, balancing functionality and aesthetics (Riggio et al., 2018).

The cradle-to-gate process for timber manufacturing is presented in

Table 3
Cradle-to-gate production process for clay soil.

Stage	Description	Inputs	Outputs	Key Features
Mineral Collection and Extraction	Manual collection of raw clay soil from natural deposits.	Manual labor	Raw clay soil (1 kg)	Labor-intensive, traditional methods.
Transportation of Raw Materials	Transporting raw clay soil to construction sites using animals.	Animal labor	Clay soil (<1 kg waste)	Low environmental impact transportation.
Mixing on Site	Preparation of clay soil by mixing it with water on-site to achieve consistency.	Human labor, water	Clay mud	Site-specific preparation phase.
Built-Up Clay Mud	On-site assembly and application of clay mud for structural components.	Human labor	Constructed clay elements	Final application phase.

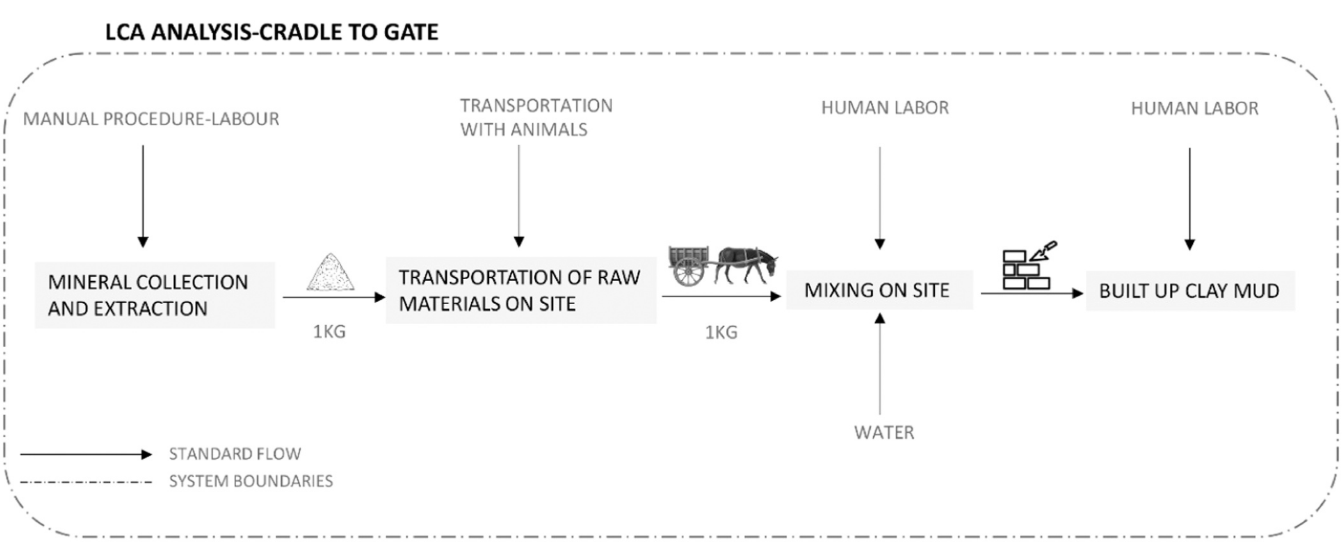

Fig. 3. Cradle-to-gate analysis of clay soil.

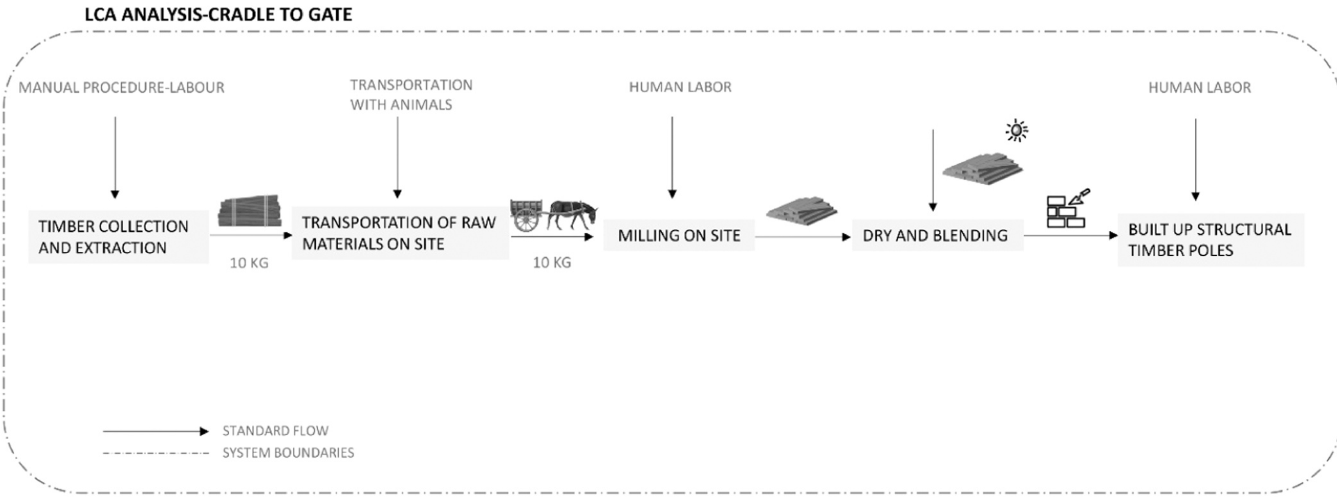

Fig. 4. Cradle-to-gate analysis of timber.

Fig. 4, focusing on its manufacturing phase and highlighting traditional, labor-intensive methods. This process is integral to the production of structural timber poles used in heritage construction and is depicted in five distinct stages within defined system boundaries. The process begins with **timber collection and extraction**, where raw timber is manually harvested from natural sources, relying entirely on traditional labor practices. A standard quantity of 10 kg of timber is collected and prepared for transport. The second stage involves the **transportation of raw materials**, where animals are used to carry the timber to construction sites. This environmentally conscious method ensures minimal impact while maintaining efficiency in material delivery. Upon arrival, the timber undergoes **milling on-site**, where human labor is employed to process the raw material into standardized pieces suitable for construction. Following this, the timber is subjected to **drying and blending**, a process that further prepares the material by reducing moisture content and enhancing its structural integrity. This stage is essential for ensuring the durability of the final product.

The process concludes with the **built-up structural timber poles phase**, where human labor is used to assemble and apply the processed timber on-site for structural purposes.

Table 4 presents the cradle-to-gate production process for timber, including a short description of the production stages, their key features as well as the input and output stages.

In contrast to standard LCI assessments, which assume mechanized processing and standardized logistics chains, the depicted process is characterized by localized extraction, manual preparation, and on-site application, leading to a distinctly different environmental profile in terms of energy input, resource intensity, and emissions potential.

Table 4
Cradle-to-gate production process for timber.

Stage	Description	Inputs	Outputs	Key Features
Timber Collection and Extraction	Manual harvesting of raw timber from natural sources.	Manual labor, 10 kg timber	Raw timber (10 kg)	Labor-intensive, traditional methods.
Transportation of Raw Materials	Transporting raw timber to construction sites using animals.	Animal labor	Timber (<10 kg waste)	Low environmental impact transportation.
Milling on Site	Processing raw timber into standardized pieces suitable for construction.	Human labor	Milled timber	Preparation for structural use.
Drying and Blending	Drying timber to reduce moisture content and improve structural integrity.	Human labor, natural drying	Dried timber	Enhances material durability.
Built-Up Structural Timber Poles	On-site assembly and application of timber for structural components.	Human labor	Constructed timber poles	Final application phase.

4.4. Lime plaster

Lime plaster was used as a protective and decorative finish for both interior and exterior walls. It was particularly effective in buildings like S1, S2, and S7, where its breathability allowed moisture to escape, protecting the underlying clay and stone structures. Its antibacterial properties also contributed to healthier indoor conditions in these residences (Vandeput, 1987).

Fig. 5 illustrates the cradle-to-gate production process for limestone plaster, focusing on its manufacturing phase and emphasizing traditional, labor-intensive methods. This process, fundamental to its application in heritage construction, is depicted in five distinct stages within the defined system boundaries. The process begins with **mineral collection and extraction**, where raw limestone is manually collected from natural deposits. This stage relies entirely on traditional manual labor, emphasizing the non-industrialized nature of the process. Once collected, a standard unit weight of 1 kg of limestone is transported to the construction site during the **transportation of raw materials** phase. Animals are used for transportation, reflecting environmentally conscious practices that produce negligible waste. Upon delivery, the material undergoes **mixing on-site**, where human labor combines the limestone with water to produce the plaster. This preparation step ensures the material achieves the desired consistency for construction purposes. The process concludes with the **limestone plaster on-site phase**, where human labor is used to apply the prepared plaster directly onto structural surfaces, finalizing the material's application for its intended purpose.

Table 5 presents the cradle-to-gate production process for lime plaster, including a short description of the production stages, their key features as well as the input and output stages.

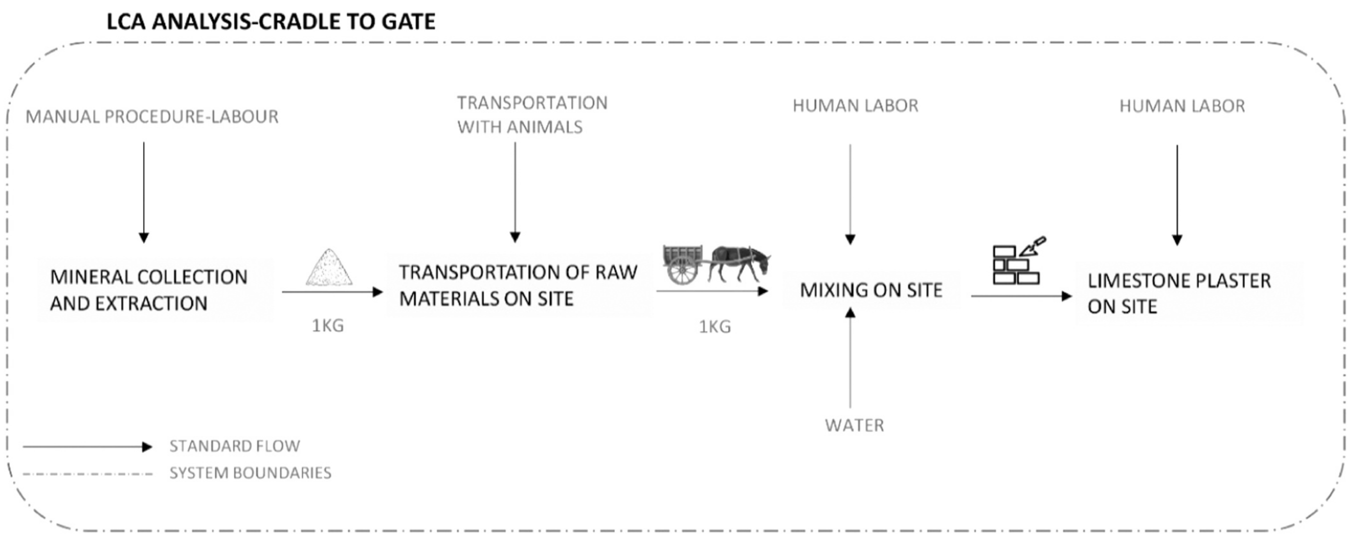

Fig. 5. Cradle-to-gate analysis of lime plaster.

Table 5
Cradle-to-gate production process for lime plaster.

Stage	Description	Inputs	Outputs	Key Features
Mineral Collection and Extraction	Manual collection of raw limestone from natural deposits.	Manual labor, 1 kg limestone	Raw limestone (1 kg)	Labor-intensive, traditional methods.
Transportation of Raw Materials	Transporting raw limestone to construction sites using animals.	Animal labor	Limestone (<1 kg waste)	Low environmental impact transportation.
Mixing on Site	Preparation of limestone plaster by mixing limestone with water on-site.	Human labor, water	Mixed plaster	Ensures consistency for application.
Limestone Plaster on Site	On-site application of prepared plaster onto structural surfaces.	Human labor	Applied limestone plaster	Final application phase.

4.5. Gypsum plaster

Gypsum plaster was employed for smooth interior finishes and decorative detailing. It is evident in S3 and S4, where its quick-setting properties allowed for intricate ornamental work. This material added an aesthetic appeal to the interiors, complementing the structural integrity provided by stone and clay (Dettmering, 2022).

The cradle-to-gate production process for gypsum plaster is illustrated in Fig. 6. This process is depicted in five distinct stages, defining the system boundaries for the manufacturing phase. The process begins with **mineral collection and extraction**, where raw gypsum is manually extracted from natural deposits. This stage relies on traditional manual procedures, ensuring a non-industrialized approach to material sourcing. Once extracted, 1 kg of raw gypsum is transported to the construction site during the **transportation of raw materials** phase. This stage employs animal labor for transportation, reflecting environmentally sustainable practices and generating negligible waste. Upon delivery, the raw gypsum undergoes **mixing on-site**, where human labor combines it with water to produce gypsum plaster. This step ensures the material achieves the correct consistency for application. The final stage, **gypsum plaster on-site**, involves human labor to apply the prepared plaster directly to structural surfaces, completing the material's transformation and use.

Table 6 presents the cradle-to-gate production process for gypsum plaster, including a short description of the production stages, their key features as well as the input and output stages.

4.6. Paint

Paint was applied to protect surfaces and enhance their visual appeal. Lime-based paints were likely used, particularly in buildings such as S2 and S8, where they provided a breathable coating compatible with the underlying lime plaster. Decorative patterns and colored finishes helped highlight architectural details, adding character to these heritage residences.

Fig. 7 illustrates the cradle-to-gate production process for lime paint, highlighting traditional and labor-intensive production methods. This process is fundamental to the application of lime paint in heritage construction and is depicted in five distinct stages within clearly defined system boundaries. The process begins with **mineral collection and extraction**, where raw limestone or other calcium-based materials are manually collected from natural deposits. This stage relies on traditional labor practices, ensuring the sustainability and simplicity of the process. Once 1 kg of raw material is collected, it is transported to the construction site in the **transportation of raw materials** phase. This transportation is carried out using animals, minimizing environmental impact and maintaining low waste generation. At the construction site, the material undergoes **mixing on-site**, where human labor combines the raw material with water to create lime paint. This step ensures that the paint achieves the desired consistency for application. The process concludes with the **lime paint on-site phase**, where human labor is used to apply the prepared paint to structural surfaces, completing its transformation and use.

Table 7 presents the cradle-to-gate production process for lime paint, including a short description of the production stages, their key features as well as the input and output stages.

The main departure from conventional LCI methodology is in the assumption of process uniformity. Standard LCIs typically represent averaged industrial processes with centralized manufacturing, long-distance transport, and high energy input. In the heritage LCI proposed in this study, each material is analyzed through a context-sensitive workflow that captures the embedded sustainability practices of the

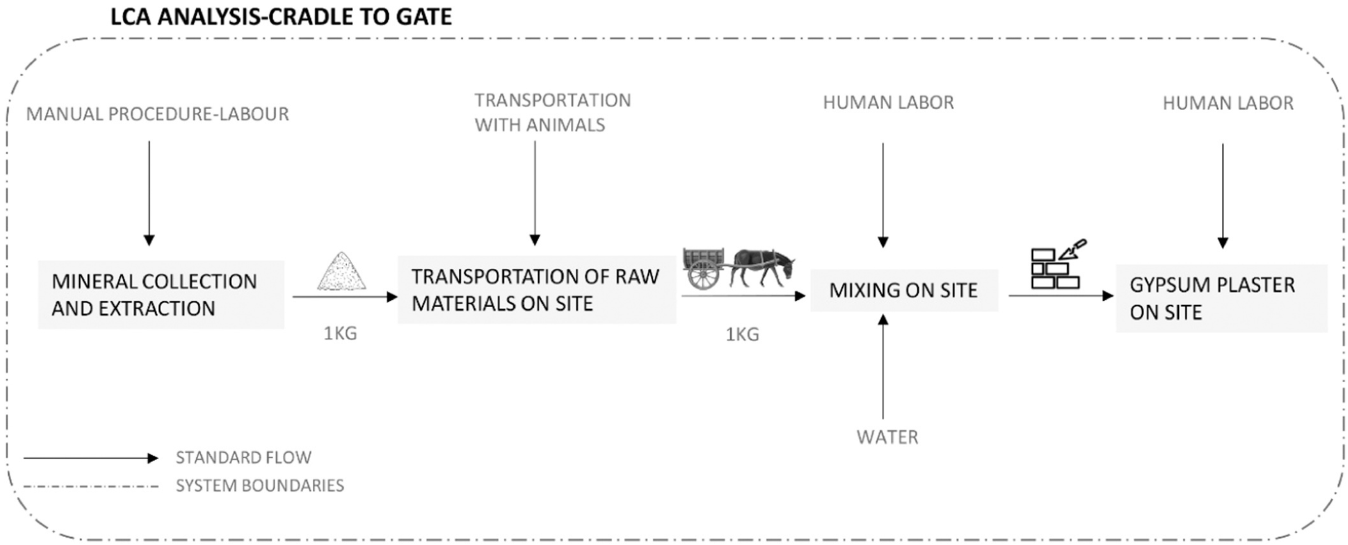

Fig. 6. Cradle-to-gate analysis of gypsum plaster.

Table 6
Cradle-to-gate production process for gypsum plaster.

Stage	Description	Inputs	Outputs	Key Features
Mineral Collection and Extraction	Manual extraction of raw gypsum from natural deposits.	Manual labor, 1 kg gypsum	Raw gypsum (1 kg)	Labor-intensive, traditional methods.
Transportation of Raw Materials	Transporting raw gypsum to construction sites using animals.	Animal labor	Gypsum (<1 kg waste)	Low environmental impact transportation.
Mixing on Site	Preparation of gypsum plaster by mixing gypsum with water on-site.	Human labor, water	Mixed gypsum plaster	Ensures consistency for application.
Gypsum Plaster on Site	On-site application of prepared gypsum plaster onto structural surfaces.	Human labor	Applied gypsum plaster	Final application phase.

past—such as low-energy curing, reuse of site materials, and absence of packaging or chemical additives. These differences underscore the need to reconsider baseline assumptions in environmental impact assessments of historic buildings.

The cradle-to-gate analysis of the primary materials used in the selected heritage buildings underscores the reliance on traditional, non-industrialized production methods. The materials—stone, clay soil, timber, lime plaster, gypsum plaster, and lime-based paint—were locally sourced and processed manually, resulting in negligible environmental impact during their production phase. This non-industrialized approach aligns with traditional construction practices, which inherently minimized embodied energy and resource consumption.

However, the absence of standardized environmental indicators for these materials presents a critical challenge. While the analysis follows the traditional ISO 14040 methodology for LCA, the framework is not equipped to fully capture the unique environmental dynamics of non-industrialized materials. The lack of quantifiable environmental impacts necessitates the development of a new methodology to accurately evaluate the sustainability of these heritage materials, addressing the gaps left by conventional LCA approaches.

4.7. Construction and Operational Phase Considerations

The methodological differentiation between the heritage-focused LCI and standard LCA practices is both structural and conceptual. While standard LCAs are calibrated to industrial systems with clear input-output datasets, the H-LCA developed in this study operates in a data-scarce environment. As a result, the evaluation draws upon process mapping, labor characterization, and site-specific observations. This leads to different assumptions about system boundaries, process efficiency, and transportation emissions. Notably, the exclusion of heavy machinery, long-distance freight, and energy-intensive manufacturing processes introduces a paradigm shift in how material impacts are assessed. The result is an alternative environmental profile that emphasizes low-intensity, decentralized construction, which cannot be captured by conventional tools and benchmarks.

Although the scope of the LCI in this study is limited to cradle-to-gate stages due to data availability, the sustainability implications of traditional construction extend into the construction and operational phases. Construction activities in heritage buildings typically involve manual labor, minimal mechanization, and site-level preparation, which contrasts with the fuel- and electricity-intensive processes of modern construction. Operationally, heritage buildings often exhibit high thermal inertia due to their massive walls and natural ventilation strategies, though they may require retrofitting to align with contemporary energy performance expectations. These characteristics suggest that traditional heritage buildings may incur lower environmental costs during construction but variable performance during operation, depending on their maintenance and usage patterns. Future work should focus on capturing and modeling these dynamics to build a full-spectrum sustainability profile.

5. Adapting level(s) for heritage building sustainability assessment

5.1. Level(s) Framework: Gaps in assessing heritage building sustainability

Level(s) is a voluntary reporting framework developed by the European Commission to promote sustainability in buildings. It aims to encourage the construction and real estate sectors to adopt practices that minimize environmental impacts, improve energy and resource efficiency, and support the transition to a more circular and sustainable economy (European Commission, 2020). Level(s) is structured around

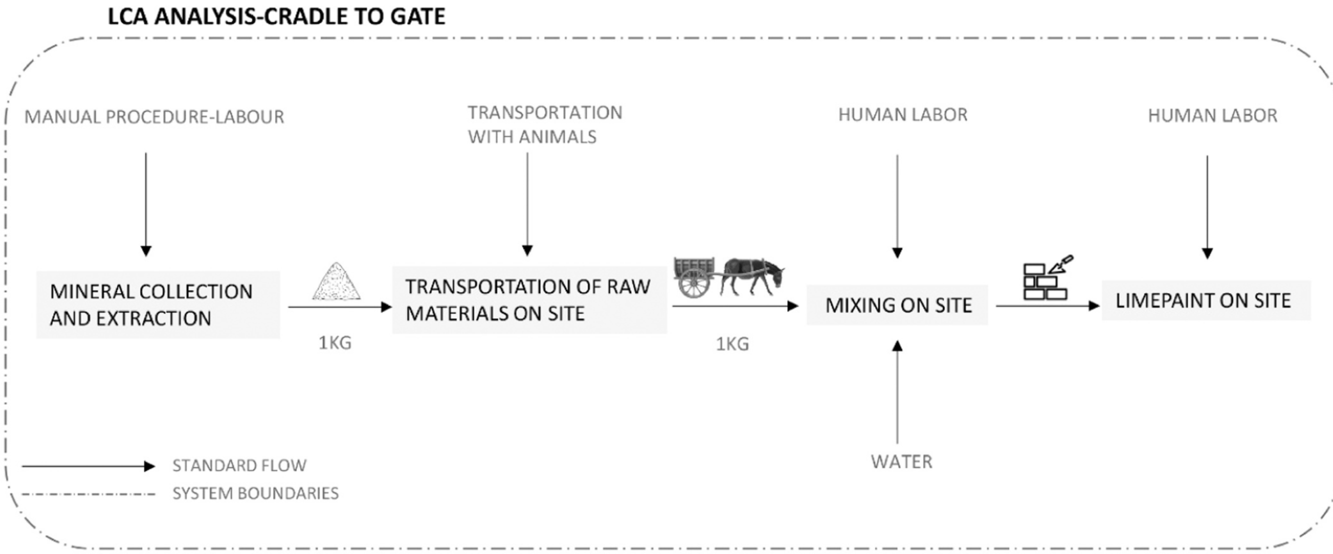

Fig. 7. Cradle-to-gate analysis of lime paint.

Table 7
Cradle-to-gate production process for lime paint.

Stage	Description	Inputs	Outputs	Key Features
Mineral Collection and Extraction	Manual extraction of raw materials (limestone or calcium-based materials).	Manual labor, 1 kg raw material	Raw material (1 kg)	Labor-intensive, traditional methods.
Transportation of Raw Materials	Transporting raw materials to construction sites using animals.	Animal labor	Lime material (<1 kg waste)	Low environmental impact transportation.
Mixing on Site	Preparation of lime paint by mixing raw material with water on-site.	Human labor, water	Mixed lime paint	Ensures consistency for application.
Lime Paint on Site	On-site application of prepared lime paint onto structural surfaces.	Human labor	Applied lime paint	Final application phase.

six **macro-objectives**, which are the key assessment dimensions for evaluating a building's sustainability:

1. **Greenhouse Gas Emissions Across the Life Cycle:** Focuses on reducing the carbon footprint of buildings, including emissions from materials, construction processes, operation, and end-of-life stages.
2. **Resource Efficient and Circular Material Life Cycles:** Promotes the efficient use of materials and encourages circular economy principles, such as recycling and reuse.
3. **Efficient Use of Water Resources:** Aims to reduce water consumption and improve water efficiency in buildings.
4. **Healthy and Comfortable Spaces:** Ensures that buildings provide good indoor environmental quality, addressing factors such as air quality, thermal comfort, and acoustic performance.
5. **Adaptation and Resilience to Climate Change:** Evaluates how well buildings can adapt to climate change impacts, such as extreme weather events.
6. **Optimized Life-Cycle Cost and Value:** Focuses on economic performance, ensuring cost-effective solutions across the building's life cycle.

Level(s) provides **common indicators** and metrics to measure performance against these macro-objectives. These indicators are aligned with existing standards (EN standards for LCA and energy performance) to ensure consistency and reliability. Level(s) offers **three levels of engagement**:

1. **Entry Level:** Basic awareness and application of sustainability principles.
2. **Intermediate Level:** More detailed assessment of specific sustainability indicators.
3. **Advanced Level:** Comprehensive life-cycle assessment (LCA) of the building.

Assessing the sustainability of heritage buildings under the **Level(s)** framework requires adaptations to address the unique characteristics of traditional materials and construction methods. While conventional **LCA** methodologies struggle with heritage materials, several **Level(s)** objectives remain partially applicable. Operational **greenhouse gas emissions** can be evaluated, but the lack of benchmarks for traditional materials hinders a full life-cycle assessment. Conversely, the inherently low embodied energy and reuse potential of heritage materials make them partially suitable for evaluating **resource efficiency** and **circular material life cycles**, even if quantification is challenging. **Healthy and comfortable spaces** are fully assessable, as parameters such as indoor air quality, thermal comfort, and acoustic performance can align with modern standards (Cakyova et al., 2021) (Exizidou et al., 2017). Similarly, the capacity of heritage buildings to adapt to **climate change impacts**—including material resilience and thermal performance—can be evaluated, providing insights into their sustainability (Xystouris et al., 2021). However, **optimized life-cycle cost and value** assessments are limited by insufficient data on the environmental impact of traditional materials. Despite this, operational cost analysis offers partial insights. Finally, **water efficiency** during retrofitting and restoration efforts can be measured, although historical water use remains unquantifiable (Annibaldi et al., 2020).

Table 8 outlines which **Level(s)** objectives can be assessed for heritage buildings, considering the unique challenges of traditional materials and the absence of standard LCA benchmarks:

Table 8
Applicability of level(s) objectives to heritage buildings.

Level(s) Objective	Applicability to Heritage Buildings
Greenhouse Gas Emissions Across the Life Cycle	Limited. The absence of LCA benchmarks for traditional materials limits full life-cycle emission assessments. However, operational energy use can be evaluated.
Resource Efficient and Circular Material Life Cycles	Partially Applicable. Traditional materials often align with circular economy principles due to reuse and low embodied energy, but detailed quantification is challenging.
Efficient Use of Water Resources	Applicable. Water usage in retrofitting or restoration activities can be assessed. Historical water efficiency may not be quantifiable.
Healthy and Comfortable Spaces	Applicable. Indoor environmental quality can be evaluated, especially for parameters like air quality and thermal comfort.
Adaptation and Resilience to Climate Change	Applicable. Heritage buildings can be assessed for their capacity to adapt to climate change impacts, such as thermal performance and material durability.
Optimized Life-Cycle Cost and Value	Limited. Detailed life-cycle costing is challenging without accurate LCA for traditional materials. Operational costs can still be analyzed.

5.2. Proposed adaptations to level(s) for heritage buildings

To ensure a comprehensive sustainability assessment of heritage buildings, tailored indicators are essential to address their unique environmental, cultural, and social dimensions. These proposed indicators capture the distinct characteristics of heritage structures, focusing on traditional materials, restoration processes, socio-cultural contributions, and energy performance. They also address gaps in conventional sustainability assessment methods and capture the cultural, historical, and environmental values of heritage buildings. By incorporating these aspects, the indicators provide a holistic framework for evaluating heritage buildings in alignment with contemporary sustainability goals.

- The **Cultural Heritage Preservation** indicator to evaluate the degree to which a building's architectural and cultural authenticity is maintained during retrofitting or restoration efforts. This ensures that historical integrity is not compromised while integrating sustainability measures.
- **Traditional Material Sustainability** to focus on the sourcing and renewability of materials like lime plaster or adobe, which are inherently sustainable. This indicator highlights the need to acknowledge these materials' environmental benefits beyond conventional life-cycle assessment (LCA) parameters.
- The **Embodied Energy of Restoration Processes** to address the energy consumed during restoration and retrofitting activities. Since heritage materials often lack life-cycle data, this indicator emphasizes the sustainability of the processes themselves.
- **Adaptive Reuse and Functional Integration** to measure how well a building adapts to modern uses without compromising its heritage value. It underscores the balance between contemporary functionality and historical preservation.
- **Material Durability and Lifecycle** to evaluate the long-term performance and maintenance cycles of traditional materials, emphasizing their resilience compared to modern alternatives.
- The **Energy Efficiency of Retrofitted Systems** to assess improvements in operational energy efficiency brought about by retrofitting measures, such as better insulation or renewable energy systems.
- The **Social and Community Impact** indicator to capture the socio-economic role of heritage buildings, focusing on their contribution to local identity and community engagement.
- The **Environmental Impact of Non-Industrialized Materials** to consider the low environmental footprint of traditional, locally sourced materials, acknowledging their minimal impact due to non-industrialized processes

Table 9 presents proposed adaptations to the Level(s) framework, aligning sustainability indicators with heritage buildings' unique characteristics, applicable objectives, and evaluation criteria.

6. Conclusions and future work

This study presents a context-sensitive adaptation of the Life Cycle Inventory approach for heritage buildings, addressing the inadequacy of existing LCA tools in capturing the sustainability attributes of traditional construction methods and materials. The framework developed departs from conventional assumptions by reconstructing material production cycles based on localized, non-industrialized practices—such as manual extraction, in situ preparation, and limited transport—thereby introducing a more accurate environmental characterization of heritage buildings. The findings indicate that heritage buildings possess distinct sustainability potential, not just in material terms, but also in construction processes that inherently avoid many of the resource-intensive practices found in modern construction. By aligning environmental assessment with cultural and historical realities, the proposed H-LCA approach fills a critical gap in heritage sustainability assessment and lays the groundwork for future frameworks that combine environmental performance with cultural value preservation.

A key challenge identified is the inadequacy of conventional Life Cycle Assessment (LCA) methodologies in evaluating the environmental performance of heritage buildings. Standardized indicators fail to capture the nuances of traditional materials and processes, leaving critical aspects, such as cultural value and restoration impacts, unquantified. This limitation is compounded by the lack of benchmark data for non-industrialized materials, which complicates their integration into existing sustainability frameworks like the European Commission's Level(s).

The gap analysis of the Level(s) framework revealed its limited applicability to heritage contexts, particularly in assessing the embodied energy of restoration processes and the socio-cultural dimensions of heritage conservation. However, the study demonstrates that several objectives within the framework—such as resource efficiency, adaptation to climate change, and indoor environmental quality—remain relevant and applicable to heritage buildings with minor modifications.

To address these gaps, the study proposes enhancements to the Level (s) framework, introducing tailored indicators for traditional materials, restoration processes, and cultural preservation. These adaptations aim to balance the environmental and cultural aspects of heritage buildings, enabling a more holistic sustainability assessment. By integrating these findings, the research provides a foundation for advancing sustainable practices in heritage preservation, ensuring these buildings contribute to contemporary environmental goals without compromising their historical integrity.

Future research shall focus on refining and validating the proposed sustainability indicators for heritage buildings. Expert panels, comprising architects, heritage conservationists, and sustainability experts, shall be convened to evaluate the relevance, applicability, and robustness of these indicators. A critical step shall involve defining specific assessment scales to ensure standardized and objective evaluations, tailored to the unique characteristics of heritage materials and processes. Additionally, the enhanced indicators and assessment methodology shall be applied to a diverse set of heritage case studies across Europe, encompassing varied climates, architectural styles, and conservation challenges.

Dataset

The dataset supporting this study, is publicly available at doi: 10.17632/szxc2gmv93.2.

Table 9
Proposed level(s) indicators for heritage building sustainability.

Category	Indicator	Rationale	Applicable Level(s) Objective	Evaluation Criteria
Cultural Heritage	Degree of preservation of architectural and cultural authenticity	Ensures heritage buildings maintain historical and cultural integrity during interventions.	Adaptation and Resilience to Climate Change	Qualitative scale: Low to High Preservation Integrity
Traditional Materials	Local sourcing and renewability of traditional materials	Acknowledges the inherently sustainable properties of traditional materials like lime plaster.	Resource Efficient and Circular Material Life Cycles	Percentage of locally sourced/renewable materials
Restoration Processes	Embodied energy of restoration and retrofitting activities	Focuses on the sustainability of processes used in conservation and retrofitting.	Greenhouse Gas Emissions Across the Life Cycle	Energy use measured in kWh/m^2
Functional Adaptability	Adaptive reuse and functional integration	Highlights the building's ability to integrate modern uses sustainably while preserving heritage.	Optimized Life-Cycle Cost and Value	Qualitative scale: Poor to Excellent Adaptation
Material Durability	Long-term performance and maintenance cycles	Emphasizes the resilience and longevity of heritage materials over time.	Adaptation and Resilience to Climate Change	Maintenance frequency (years) and material lifespan
Energy Efficiency	Energy efficiency of retrofitted systems	Measures operational energy savings from interventions like insulation or renewable systems.	Greenhouse Gas Emissions Across the Life Cycle	Percentage reduction in energy use
Social and Community Impact	Contribution to local cultural identity and community engagement	Recognizes the socio-economic role of heritage buildings in supporting community values.	Healthy and Comfortable Spaces	Community engagement index: Low to High
Environmental Impact	Environmental footprint of non-industrialized materials	Accounts for the low-impact, traditional methods of producing heritage building materials.	Resource Efficient and Circular Material Life Cycles	Carbon footprint measured in CO_2e/m^2

Any additional data used in the study may be provided upon reasonable request to the author.

CRediT authorship contribution statement

Paris A Fokaides: Writing – original draft, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of Competing Interest

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

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Data availability

I have shared the dataset used under Mendeley dataset.

References

Annibaldi, V., Cucchiella, F., De Berardinis, P., Gastaldi, M., Rotilio, M., 2020. An integrated sustainable and profitable approach of energy efficiency in heritage buildings. J. Clean. Prod. 251, 119516.
Artopoulos, G., Fokaides, P., Lysandrou, V., Deligiorgi, M., Sabatakos, P., Agapiou, A., 2024. Data-driven multi-scale study of historic urban environments by accessing earth observation and non-destructive testing information via an HBIM-supported platform. Int. J. Archit. Herit. 18 (6), 920–939.
Cakyova, K., Figueiredo, A., Oliveira, R., Rebelo, F., Vicente, R., Fokaides, P., 2021. Simulation of passive ventilation strategies towards indoor CO2 concentration reduction for passive houses. J. Build. Eng. 43, 103108.
Christoforou, E., Kylili, A., Fokaides, P.A., Ioannou, I., 2016. Cradle to site Life Cycle Assessment (LCA) of adobe bricks. J. Clean. Prod. 112, 443–452.
Dettmering, T., 2022. Historical plasters in connection with thermal insulations. In Energy-Efficient Retrofit of Buildings by Interior Insulation. Butterworth-Heinemann, pp. 53–74.
European Commission. (2020). Level(s) – A common EU framework of core sustainability indicators for office and residential buildings – Parts 1 and 2: Introduction to Level(s) and how it works. Publications Office of the European Union. ⟨https://ec.europa.eu/environment/topics/circular-economy/levels_en⟩. Last accessed 27 Dec 2024.
Exizidou, P., Christoforou, E., Fokaides, P.A., 2017. Numerical assessment of night ventilation impact on the thermal comfort of vernacular buildings. J. Build. Pathol. Rehabil. 2, 1–11.
Fokaides, Paris, 2024. "Dataset for Advancing Sustainability in Heritage Buildings: Case Studies of Eight Heritage Buildings in Cyprus for the Development of the Heritage Life Cycle Assessment (H-LCA) Framework". Mendeley Data V2. https://doi.org/10.17632/szxc2gmv93.2.
Jiménez de Madariaga, C., 2021. Dry stone constructions–intangible cultural heritage and sustainable environment. J. Cult. Herit. Manag. Sustain. Dev. 11 (4), 614–626.
Klumbyte, E., Georgali, P.Z., Spudys, P., Giama, E., Morkunaite, L., Pupeikis, D., Fokaides, P., 2023. Enhancing whole building life cycle assessment through building information modelling: Principles and best practices. Energy Build. 296, 113401.
Lidelöw, S., Örn, T., Luciani, A., Rizzo, A., 2019. Energy-efficiency measures for heritage buildings: A literature review. Sustain. Cities Soc. 45, 231–242.
Mazzetto, S., 2024. Comparative Life Cycle Assessment of Traditional and Modern Materials in Heritage Building Restoration: A Case Study from Ushaiger Village. In: Sustainability, 17, p. 25.
Munarim, U., Ghisi, E., 2016. Environmental feasibility of heritage buildings rehabilitation. Renew. Sustain. Energy Rev. 58, 235–249.
Nair, G., Verde, L., Olofsson, T., 2022. A review on technical challenges and possibilities on energy efficient retrofit measures in heritage buildings. Energies 15 (20), 7472.
Riggio, M., D'ayala, D., Parisi, M.A., Tardini, C., 2018. Assessment of heritage timber structures: Review of standards, guidelines and procedures. J. Cult. Herit. 31, 220–235.
Spudys, P., Osadcha, I., Morkunaite, L., Manhanga, F.C., Georgali, P.Z., Klumbyte, E., Fokaides, P., 2024. A comparative life cycle assessment of building sustainability across typical European building geometries. Energy 302, 131693.
Vandeput, L., 1987. Splitting techniques in quarries in the Eastern Mediterranean. Acta Archaeol. Lovan. 26-27, 81–107.
Xystouris, K., Apostolidou, E., Kylili, A., Fokaides, P.A., 2021. The effect of climate change on weathering: evidences from heritage buildings under subtropical conditions. J. Sustain. Archit. Civ. Eng. 29 (2), 232–245.
Zhao, C., Zhang, Y., Wang, C.C., Hou, M., Li, A., 2019. Recent progress in instrumental techniques for architectural heritage materials. Herit. Sci. 7, 1–50.