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Research paper

A METHODOLOGICAL FRAMEWORK FOR INTEGRATED LIFE CYCLE ASSESSMENT AND LIFE CYCLE COST OF PASSIVE ENERGY RENOVATION OF RESIDENTIAL BUILDINGS IN SERBIA

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Abstract

This paper develops a methodological framework for the integrated assessment of life cycle assessment (LCA) and life cycle costs (LCC) in the decision-making process for passive energy renovation of multi-family residential buildings in Serbia. The proposed framework enables a systematic selection of building materials and components for energy renovation, taking into account both the environmental footprint and the total costs over the life cycle of the building after renovation. The methodological framework consists of seven steps. The first step involves calculating the operational energy of the existing building, analyzing the total energy consumption required for the building's functionality, including heating, cooling, ventilation, lighting, and electrical appliances. Next, passive energy renovation scenarios are defined, and various material and assembly proposals for improving energy efficiency are formulated. The next step involves calculating the embodied energy for each renovation scenario, considering the energy required for material extraction, production, transportation, installation, maintenance, and recycling. This is followed by a simulation-based calculation of operational energy for each renovation scenario and the determination of potential energy savings. Subsequently, the environmental impact of materials is evaluated through a life cycle assessment of selected materials and assemblies. In parallel with the life cycle assessment, a life cycle cost analysis is conducted to assess the long-term economic aspects of energy renovation from the moment of renovation until the end of the building's life cycle. Finally, the results are integrated to support optimal decision-making by analyzing all previous steps to determine the best material choices for achieving both environmentally and economically sustainable energy renovation. The aim of this research is to provide an applicable framework for assessing the environmental impacts and life cycle costs of a building from the renovation phase to the end of its life cycle, facilitating the advancement of sustainable energy renovation strategies for multi-family residential buildings.

Key words: *Energy renovation, methodological framework, life cycle assessment (LCA), life cycle cost (LCC), operational energy, embodied energy*

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1. INTRODUCTION

The construction sector is the largest energy consumer in Europe, being responsible for 40% of total energy consumption and 36% of greenhouse gas emissions, while 75% of existing buildings are energy inefficient, and it is estimated that 85–90% of these buildings will still exist in 2050 [1]. The renovation of the existing housing stock is a key factor in meeting the targets set by the European Commission for the period up to 2050 through the European Green Deal strategy [2]. This ambitious strategy, adopted in 2019, relies on the Energy Efficiency Directive (DIRECTIVE (EU) 2018/844) and the Energy Performance of Buildings Directive (EPBD (EU) 2024/1275) as legislative frameworks for reducing energy consumption and greenhouse gas emissions, with an emphasis on achieving climate neutrality across the entire economy by no later than 2050 [3].

With the implementation of the "Fit for 55" legislative package developed to support these strategies, which requires a reduction of net greenhouse gas emissions by at least 55% compared to 1990 levels by 2030, and the decarbonization of the building stock by 2050 [4], the targets are no longer limited to reducing emissions caused by the operational energy of buildings—i.e., the energy required for their functioning—but are instead oriented toward the entire life cycle of buildings, encompassing both embodied and operational energy throughout the building's life span. In addition, the revised Energy Performance of Buildings Directive promotes the assessment of life cycle performance during building renovation [3]. The Directive emphasizes that life cycle performance assessment should be an integral part of both new construction and the renovation of existing buildings, requiring the inclusion of policies to reduce emissions throughout the entire life cycle in national building renovation plans of EU Member States.

Moreover, the Directive expects EU Member States to define minimum requirements for the energy performance of buildings and building elements, taking into account the achievement of an optimal balance between investment and energy savings over the life cycle of the building [3].

Although Serbia is not an EU member state, it has committed to the Green Agenda for the Western Balkans, which extends the EU Renovation Wave to the Western Balkans [5]. Based on Serbia's membership in the Energy Community, a Long-Term Strategy for Promoting Investment in the Renovation of the National Building Stock of the Republic of Serbia until 2050 has been adopted, aiming to define measures for building renovation [6]. The strategy promotes the energy renovation of residential and commercial buildings, with a focus on major renovation, to reduce primary and final energy consumption. According to the current Rulebook on Energy Efficiency of Buildings in Serbia, major renovation is defined as adaptation or rehabilitation works whose value amounts to at least 25% of the value of the building with land, or if at least 25% of the building envelope is subject to energy refurbishment [7].

According to research conducted during 2011 and 2012 as part of the project for the classification of multi-family residential buildings in Serbia, which was aligned with the methodology of the international TABULA project, it was determined that the multi-family residential stock in Serbia has poor energy performance. The research results indicate a pronounced need for the implementation of energy refurbishment measures to reduce operational energy consumption in this significant segment of the building stock, as well as to improve overall energy efficiency in the residential sector [8].

2. METHODOLOGY

The methodological framework for integrated life cycle assessment (LCA) and life cycle cost (LCC) analysis in the decision-making process for passive energy renovation of multi-family residential buildings in Serbia comprises seven steps (Fig. 1).

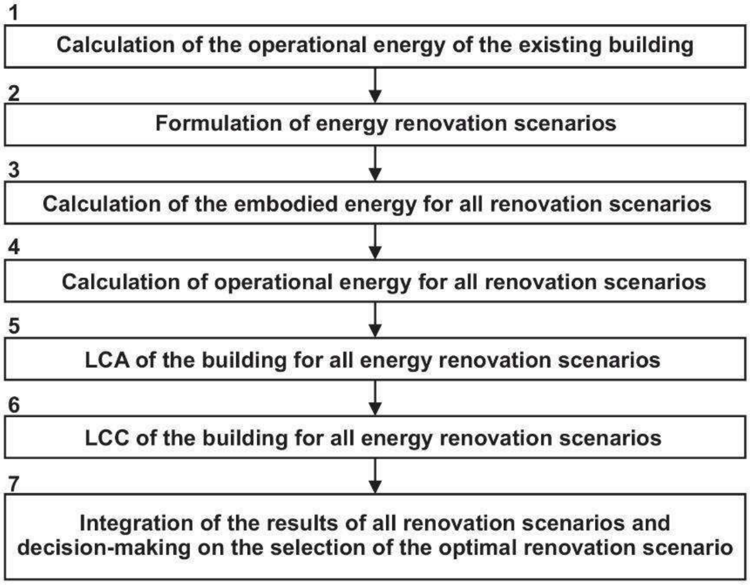

Figure 1. Diagram of the methodological framework for integrated life cycle assessment (LCA) and life cycle cost (LCC) analysis in the decision-making process for passive energy renovation of buildings

2.1. LCA assessment in the context of building energy renovation

Life cycle assessment (LCA) is a structured, comprehensive, and internationally standardized method for evaluating the environmental impacts of a product, process, or service throughout its entire life cycle [9]. In the context of building energy renovation, LCA enables the identification and quantification of environmental burdens associated with the production of construction materials, transportation, installation, use and maintenance of systems, as well as the demolition and disposal phases. By applying this method, it is possible to objectively assess the contribution of various energy efficiency strategies to the reduction of greenhouse gas emissions, primary energy consumption, resource depletion, and other relevant environmental indicators.

The international standards ISO 14040 and ISO 14044 define the fundamental methodology for conducting life cycle assessment. The LCA process includes four main phases: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation of results [9, 10].

In the context of building energy renovation, the goal of the assessment is to evaluate the life cycle of a building after renovation. This analysis involves assessing the life cycle of all materials applied during the renovation, which constitute the inventory (LCI). The environmental impact is then assessed using specific impact categories. For building impact assessment in Europe, the CML impact assessment methodology is applied, as prescribed by European standards EN 15978 and EN 15804.

When defining the subject of the LCA, it is necessary to consider the function of the product—which, in this case, is a multi-family residential building—the functional unit, the structure of the product system, and the system boundaries. The functional unit is the basic measure of performance that the product should achieve. In the case of building energy renovation, the most commonly used functional unit is one square meter of heated floor area.

For building life cycle assessment, the system boundaries of the building life cycle are defined by standard EN 15804 and include the life cycle stages illustrated in Figure 2 [11].

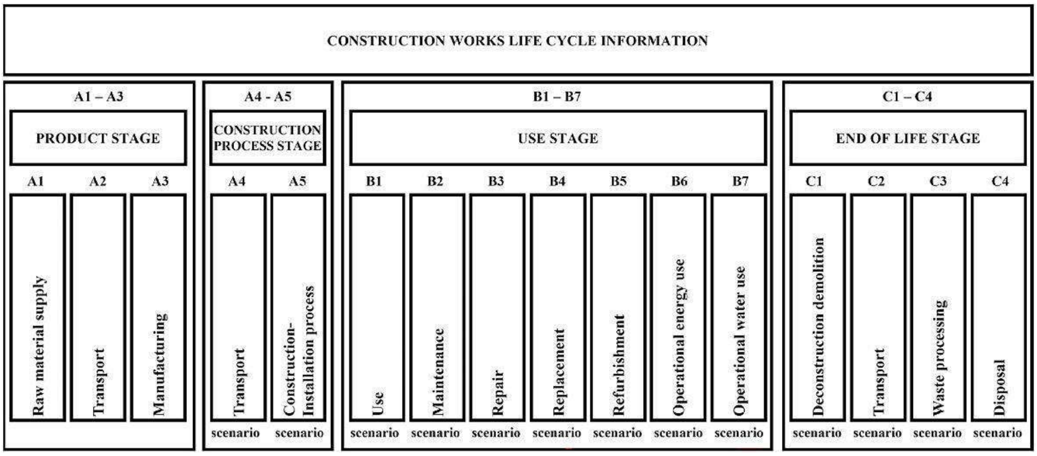

Figure 2. Life cycle stages and modules according to EN 15804 [11]

Modules A1–A3 are referred to as the **Product Stage**, also known as "cradle to gate." This stage includes all impacts associated with raw material extraction (A1), transportation of raw materials to the factory (A2), and the manufacturing of construction products (A3).

Modules A4–A5 represent the **Construction Process Stage** and cover all impacts related to the transportation of materials to the construction site (A4) and on-site activities associated with installation, including waste generation and its disposal (A5).

Modules B1–B7 comprise the **Use Stage**, which includes all impacts associated with the use of the building throughout its life cycle (B1), maintenance (B2), repair (B3), replacement (B4), refurbishment (B5), operational energy use (B6), and operational water use (B7).

Modules C1–C4 represent the **End-of-Life Stage**, which includes the deconstruction and demolition of the building (C1), impacts from transportation to waste processing facilities (C2), waste processing for reuse and recycling (C3), and final disposal (C4) [11].

2.2. LCC assessment in the context of building energy renovation

Life Cycle Cost Analysis (LCC) is a method for assessing the total costs of a building, taking into account all expenses—from raw material extraction, transportation of raw materials to manufacturing facilities, production of building materials, transportation of materials, construction of the building, usage, to its demolition. LCCA is particularly useful when comparing design alternatives that meet the same performance criteria but differ in initial and operational costs, in order to select the option that maximizes net savings. LCCA should be conducted early in the design process, while changes can still be made to reduce life cycle costs [12].

Over the years, numerous economic evaluation methods associated with LCC have emerged. Commonly used methods include: Simple Payback Period (SPP), Discounted

Payback Period (DPP), Equivalent Annual Cost (EAC), Internal Rate of Return (IRR), Net Savings (NS), and Net Present Value (NPV) [13]. Among these, ISO 15686-5, the standard for life cycle costing of buildings, recommends the use of the Net Present Value (NPV) method. NPV represents the difference between the present value (PV) of future cash flows generated by an investment and the initial investment cost. It is calculated based on a fixed standard discount rate over the assessment period, typically 5%. The PV reflects the value of cash flows generated at one or more points in time, expressed in today's terms. In other words, it is the value of future funds discounted to the present using a defined interest rate. If the cash flow occurs in the future, the calculation accounts for the time value of money by discounting it. Calculating PV enables comparative analysis of cash flows occurring at different times.The NPV method is widely used to evaluate the profitability or level of return of an investment project and is a commonly applied tool for project valuation. The viability of an investment idea is determined by calculating the NPV of the project. If the result is positive, the project is financially viable. If negative, the project is not financially viable. When multiple options exist within an investment project, the NPV should be calculated for each alternative with the same initial investment, and their results compared. Generally, the investor should select the option with the highest NPV, as it represents the most valuable investment from a financial standpoint [12, 13].

There are many different costs associated with the construction, use, maintenance, and demolition of a building. These costs are usually categorized as follows: initial costs (construction costs), operating costs, maintenance and repair costs, replacement costs, and demolition costs. Only those costs within each category that are relevant to the decision and significant in amount are necessary for making a valid investment decision. Costs are relevant if they differ between alternatives, and significant if they are large enough to impact the project's total LCC. All costs are entered in today's prices; the LCCA method accounts for their escalation to the year of occurrence and then discounts them back to the base year to obtain their present value [12].

3. RESULTS

The following text presents the methodological framework for integrated Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) evaluation in the decision-making process for passive energy renovation of multi-family residential buildings in Serbia. The framework comprises seven steps, with each step explained in more detail according to the established methodology.

1. Calculation of the operational energy of the existing building

The first step corresponds to module B1 and involves calculating the total operational energy consumption of the existing building. Operational energy refers to the energy required for the functionality of a residential building, including heating, cooling, ventilation, domestic hot water preparation, lighting, and the operation of electrical appliances. According to current energy efficiency regulations for buildings in Serbia, only heating energy consumption is considered when determining a building's energy class [7]. This limitation arises from the lack of developed tools for calculating total operational energy. Although heating energy accounts for the largest share of operational consumption, other types of energy use must not be neglected. For more reliable and comprehensive assessments, it is recommended to calculate the total operational energy using building energy simulation software, such as EnergyPlus.

2. Formulation of energy renovation scenarios

The formulation of energy renovation scenarios represents the second step in the integrated assessment process. In this step, variants for improving the building's thermal envelope are created in accordance with the characteristics of its individual components, as presented in Table 1.

Table 1. Criteria for determining the significance and potential for improving the thermal envelope positions

No.	Criterion	Impact Description
1	Surface area of the envelope position	Larger surfaces have a greater impact on total energy losses.
2	Degree of transmission heat loss	High U-values indicate significant thermal losses.
3	Position of the element (external/internal)	External elements are in direct contact with outdoor conditions.
4	Condition and deterioration level	Deteriorated components require urgent and more extensive renovation.
5	Impact on indoor comfort and living quality	Direct influence on thermal comfort, acoustic insulation, indoor air quality, and occupant satisfaction.
6	Potential for integration of additional energy systems (e.g., photovoltaics panels, ventilated facades)	Increases overall sustainability of the building, especially when combined with passive and active systems.
7	Type of element (transparent/opaque)	Transparent elements have specific characteristics and contribute to solar gains.
8	Spatial availability for additional insulation	Limited space may constrain the choice of material or insulation thickness.
9	Possibility for phased implementation	Enables more flexible and cost-efficient renovation strategies.
10	Orientation of the envelope position	North-facing elements have higher losses; south-facing can contribute to passive solar gains.
11	Cultural protection status	Limits the scope of interventions and requires specific conservation-compliant solutions.
12	Accessibility for renovation works	Hard-to-reach areas increase the complexity and cost of construction works.

Based on the identification of elements of the thermal envelope with the greatest potential for improvement, the formulation of energy renovation scenarios is approached. In this phase, renovation variants are defined, and the selection of appropriate materials and technologies for renovation is carried out. The key issue becomes the selection of materials and the criteria according to which the selection is made. The choice of materials for energy renovation must include multiple criteria listed in Table 2.

Table 2. Criteria for the selection of materials and products for energy renovations

No.	Criterion	Impact Description
1	Thermal conductivity (λ-value)	Lower values indicate better insulation and reduced heat loss.
2	Thermal mass / heat storage capacity	Higher capacity contributes to thermal stability of indoor environments.
3	Vapor permeability	Important for preventing condensation and maintaining hygrothermal comfort.
4	Resistance to moisture, mold, and biological agents	Improves durability and reduces health risks.
5	Fire resistance	Material must meet fire safety standards.
6	Material lifespan	Longer lifespan reduces the need for replacement and overall impacts.
7	Origin of material (natural / synthetic)	Natural materials often have lower environmental impact but differing performance.
8	Local availability	Reduces transport emissions and costs.
9	Material cost	Directly affects the financial feasibility of renovation scenarios.
10	Ease of installation and disassembly	Enables fast installation, lower labor costs, and potential reuse.
11	Recyclability and reusability	Determines end-of-life impacts and waste generation.
12	Impact on indoor environmental quality (e.g., VOC emissions)	Important for occupant health and indoor air quality.
13	Compatibility with cultural heritage protection	Material must be aligned with conservation requirements.
14	Compliance with standards and regulations	Necessary for legal application and potential subsidies.

It is recommended to form several clearly differentiated variants of renovation scenarios in order to precisely identify which option offers the optimal balance between ecological sustainability and economic feasibility through the subsequent phases of analysis, including life cycle assessment (LCA) and life cycle cost (LCC) evaluation.

3. Calculation of the embodied energy for all renovation scenarios

This step analyzes the energy footprint associated with the production and implementation of materials before the building begins functioning. The embodied energy analysis is carried out through a systematic series of steps that quantify the energy expended during the entire production and installation process of materials proposed for the energy renovation scenarios. The first step in this analysis is the identification and quantification of all construction materials and products used in each renovation scenario, achieved by preparing a detailed bill of quantities. For each building component, the material type, thickness, density, unit measure, and total quantity are precisely defined. Next, for each material, the specific embodied energy data (measured in MJ/kg, MJ/m², or MJ/m³) is taken from relevant databases (e.g., Ecoinvent[3]), which includes the energy expended for raw material extraction (module A1), transport and processing (A2), production (A3), transportation to the construction site (A4), and installation (A5). The total embodied energy for a given material is calculated by multiplying its specific value by the quantity of material intended for each scenario.

If specific materials have a shorter lifespan than the overall time horizon of the analysis, their replacement is planned under module B4, and the additional energy consumption is included in the overall balance for that scenario. All data is then summed by scenario and compared to identify those scenarios with the lowest total embodied energy.

4. Calculation of operational energy for all renovation scenarios

This step of the methodological framework concerns the calculation of operational energy for all renovation scenarios, estimating the amount of energy needed for the building's operation over its useful life after renovation. This analysis includes energy consumption for heating, cooling, ventilation, domestic hot water preparation, lighting, and electrical devices. In contrast to the initial estimate of operational energy for the existing state (step 1), energy simulations are carried out for each defined improvement scenario, allowing for a precise prediction of the effects of proposed solutions on the building's future energy efficiency. Simulations are performed using validated software tools for modeling building energy performance, such as DesignBuilder, EnergyPlus, or other BIM-based tools integrated with energy modules. The building model is updated according to each individual scenario—in terms of thermal properties of the envelope, types and thicknesses of insulation materials, window and door quality, and any additional passive measures. Furthermore, the data input includes local climate conditions, building usage profiles, heating and cooling regimes, and technical system characteristics.

In this phase, the predicted consumption of primary and final energy for each energy use is quantified and expressed in kWh/m² per year. The results allow for the comparison of scenarios in terms of operational energy consumption reduction and overall contribution to the building's energy efficiency.

5. LCA of the building for all energy renovation scenarios

This step involves the life cycle assessment of the building after the simulated renovation, in accordance with the defined renovation scenarios. This analysis corresponds to the full scope of the LCA methodology "from cradle to grave," as it includes the assessment of the entire life cycle of the materials used in the renovation, as well as the building itself, from the point of renovation to the end of its life cycle.

This step includes a life cycle inventory (LCI) analysis, which quantifies all materials and products proposed in the renovation scenarios. An environmental impact assessment (LCIA) is then performed for the phases of material production, transportation, and installation (modules A1–A5). Special attention is given to evaluating the durability of the selected

[3] Ecoinvent v3 is an LCI database with global spatial coverage regionalized by country or continent.

materials. If the lifespan of a proposed material is shorter than the projected lifespan of the renovated building, its replacement during the usage phase (module B4) within the analyzed time horizon should be considered. This ensures a realistic and representative depiction of potential impacts throughout the entire exploitation period.

Additionally, the end of life for the applied materials and the entire building (modules C1–C4) is analyzed. This phase is particularly complex because it encompasses all materials and components installed in the building, representing the most comprehensive segment of the LCA analysis.

The environmental impact assessment is carried out according to the CML impact assessment methodology, which includes thirteen environmental impact categories, such as global warming, ozone depletion, and resource depletion [14].

The LCA analysis is performed using a bill of quantities with material quantities, so all applied materials are standardized to a common unit—kilogram.

6. LCC of the building for all energy renovation scenarios

The life cycle cost (LCC) evaluation of the building is the fourth step of the methodological framework and directly follows the previous LCA analysis. The net present value (NPV) method is used in this phase, which involves discounting all future costs to the current time to /material prices, on the final results.

The LCC analysis includes all costs arising during the building's life cycle. Investment costs encompass the procurement and installation of building materials and systems specified for each energy renovation scenario, as well as transportation, construction works, site organization, and all associated design, supervision, and logistics costs. Furthermore, the analysis takes into account usage and maintenance costs, including periodic repairs and potential replacement of components with a shorter lifespan than the overall analyzed period. In this regard, it is crucial to account for material replacements if their durability does not cover the entire designed lifespan of the building, which is calculated as an additional future cost in the LCC analysis under module B4.

The analysis also includes operational costs, primarily energy costs, which are estimated based on the energy consumption simulation results for each renovation scenario. This quantifies the long-term savings each scenario offers, directly affecting the return on investment. If data is available, end-of-life costs—such as deconstruction, transportation, recycling, or disposal of materials—can also be included, providing a more complete economic picture.

The analysis is performed for a period of ten years, which is a common horizon for assessing the profitability of energy renovations, particularly from an investment decision-making perspective. Within this period, the payback period of initial investments is determined, comparing scenarios and identifying the one that offers the fastest or most favorable financial effect relative to its ecological contribution.

7. Integration of the results of all renovation scenarios and decision-making on the selection of the optimal renovation scenario

This step consolidates the data obtained through the life cycle assessment (LCA), life cycle cost (LCC) analysis, and embodied and operational energy calculations. The results are compared to identify the variant that offers the best balance between ecological sustainability, economic feasibility, and technical justification. The decision on the optimal scenario is made based on an integrated approach that involves evaluating and weighting various indicators according to predefined decision-making criteria.

4. DISCUSSION

The development of a methodological framework for integrated life cycle assessment (LCA) and life cycle cost (LCC) analysis in the context of passive energy renovation of multi-family residential buildings in Serbia raises important questions about the complexity of the decision-making process, which must simultaneously consider the ecological, economic, and technical aspects of renovation. In Serbia, practice still largely relies on simple energy efficiency indicators, limited mainly to heating energy consumption. Therefore, the significance of this work is crucial as it highlights the need to expand the analytical framework to include other forms of energy consumption, as well as the impacts of materials and processes across all life cycle stages. Unlike many EU countries, where building sustainability assessments are increasingly based on frameworks like Level(s) [15] and the Renovation Wave initiative [16], Serbia still lacks fully developed tools to assess environmental and economic performance throughout a building's life cycle. In addition to these well-known frameworks, many European research and innovation projects have played an important role in improving methods and adding both LCA and LCC into building assessments. Projects like ENSLIC – Building (a pilot project under Intelligent Energy Europe), SuPerBuildings, and OPEN HOUSE have made significant contributions by creating metrics, indicators, and comprehensive models that consider the entire life cycle [17]. The results of these projects have helped develop new standardized tools and methods that are now widely used in many EU countries. While EU countries are moving towards flexible assessment methods that include circularity metrics, Serbia still mainly focuses on traditional energy performance improvements. This difference highlights the need to adapt international methods to the local context while aligning more with the EU's broader sustainability goals.

The implementation of the proposed methodological framework faces challenges such as the availability and reliability of data for both LCA and LCC analyses. At the national level, there is still no developed system of databases for construction materials with local environmental indicators, which forces the analysis to rely on international databases (such as Ecoinvent) that do not fully reflect the local context. Additionally, accurate cost prediction in LCC analysis requires stable and regularly updated data on market prices of materials, energy, and labor, which, under conditions of economic instability, presents an additional obstacle. Despite these challenges, the methodological framework developed in this paper has the potential to become the foundation for more rational planning and implementation of energy renovations, enabling decision-making based on quantitative assessments that lead to sustainable and long-term cost-effective solutions. Furthermore, future research is needed to further validate the framework through concrete case studies. It is important to emphasize that the methodological framework presented in this paper should not be seen as a static model, but as a dynamic tool that can be developed and improved in accordance with advances in technology, standards, and societal demands.

5. CONCLUSIONS

This paper develops a methodological framework for the integrated assessment of life cycle analysis (LCA) and life cycle cost (LCC) as a support tool for the decision-making process in the field of passive energy renovation of multi-family residential buildings in Serbia.

The proposed framework provides a systematic approach to evaluating the environmental and economic performance of different renovation scenarios, considering both operational and embodied energy, as well as all life cycle stages—from the production and installation of materials to their maintenance, replacement, and disposal.

Through seven steps, the framework enables the precise identification of the optimal renovation scenario that achieves the best balance between reducing environmental impact, lowering operational costs, ensuring technical feasibility, and ensuring long-term sustainability. The application of this methodological framework can contribute to improving energy efficiency strategies at the building level and can also serve as a tool for enhancing public policies related to energy renovation, investment planning, and the promotion of sustainable construction. Additionally, such an approach enables more rational decision-making, thereby increasing the likelihood of implementing energy renovations that are both environmentally justified and economically sustainable. In this way, it contributes to the development of a more resilient, energy-efficient, and climate-responsible existing housing stock in Serbia.

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