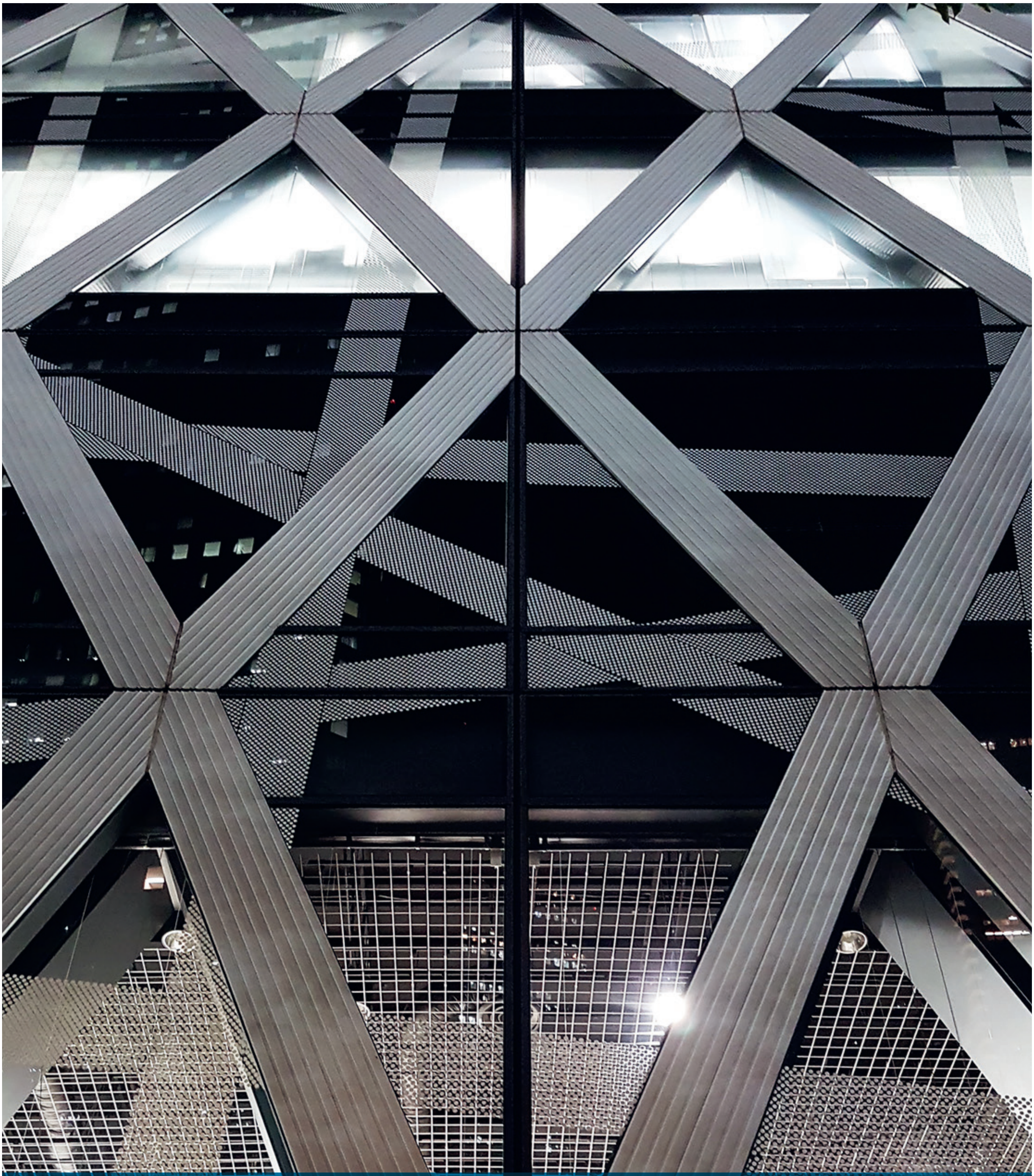

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CONSTRUCTION AND ITS INTERCONNECTIONS

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Cover illustration: Mode Gakuen Cocoon Tower in the Nishi-Shinjuku district (Tokyo, Japan) by Kenzō Tange, external view. © Riccardo Gulli, 2018

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EXPEDITIVE METHOD FOR BALANCING ENERGY, ENVIRONMENT, AND COSTS IN SUSTAINABLE BUILDING REGENERATION: APPLICATION TO A PREFABRICATED SCHOOL IN BOLOGNA

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Abstract

Renovating the existing school building stock requires fast, transparent decisions that balance energy, environmental, and economic outcomes. We present S.C.O.R.E.S. (Sustainable Construction or Renovation Easy Scoring), a rapid multi-criteria tool that integrates modeled energy demand, life-cycle indicators – including biogenic carbon in line with EN 15804 – and life-cycle costs to rank alternative scenarios. The tool is demonstrated on a public school in Bologna (Italy), comparing a baseline and three intervention packages. Results show that envelope and HVAC upgrades can reduce delivered energy and global warming potential substantially while maintaining acceptable life-cycle costs; sensitivity analysis confirms the robustness of rankings to weights and benchmarks. We discuss how S.C.O.R.E.S. supports early-stage design and policy by making trade-offs explicit, documenting assumptions, and enabling reproducible comparisons. The paper provides (i) a transparent scoring framework with open benchmarks, (ii) its application to a relevant building type, and (iii) guidance to interpret results in terms of energy, environment, and costs. The approach aims to assist policymakers, designers, and school owners in prioritizing renovation strategies under time and data constraints.

Keywords

Public school building stock, Sustainable regeneration strategies, Biogenic carbon, Life-Cycle Assessment (LCA), Life-Cycle Cost (LCC).

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1. INTRODUCTION

1.1. THE CHALLENGES OF ENERGY AND SEISMIC RETROFIT IN ITALIAN SCHOOL BUILDINGS

The European Union (EU) has set ambitious goals for reducing greenhouse gas emissions from the building sector, which accounts for 36% of CO_2 emissions and 40% of total energy consumption. Additionally, 10% of emissions come from embodied carbon in building materials [1]. Given these impacts, the EU has introduced policies such as the Energy Performance of Buildings Directive (EPBD), the Renovation Wave strategy, and various financial programs to accelerate energy-efficient renovations [2, 3]. Achieving climate neutrality by 2050 requires a combination of emission reductions, energy efficiency improvements, increased use of renewable energy, and sustainable construction practices [4].

The Italian school building stock plays a crucial role in this effort. With over 41,000 school buildings, the sector is responsible for 9.5 TWh/y in thermal energy consumption and 3.66 TWh/year in electricity use. A significant portion of these buildings was constructed before 1975 [5], predating the first national energy performance regulations, introduced by Law No. 373 of March 30, 1976, "Standards for the containment of energy consumption for thermal uses in buildings" (*Norme per il contenimento del consumo energetico per usi termici negli edifici*) [6]. As a result, these schools lack thermal insulation, use outdated Heating, Ventilation, and Air Conditioning (HVAC) systems, and generally have poor energy performance, making them major contributors to energy waste and carbon emissions [7]. In addition to energy performance, the school building stock has deficiencies related to seismic safety, which affects both the oldest masonry buildings, distinguishing the historic centers, and those of more recent construction, made of reinforced concrete. Among the latter, special attention should be paid to prefabricated structures, which constitute the majority of Italy's school heritage built during the 1960s-1980s [5]. These structures, due to their construction concept, present intrinsic seismic vulnerabilities resulting from the use of dry joints, as well as the lack of standards regulating their structural design, which includes not only static but also dynamic seismic behavior. In fact, it must be considered that, in Italy, the first seismic legislation was Law No. 64 of February 2, 1974, "Provisions for constructions with special requirements for seismic zones" (*Disposizioni per le costruzioni con requisiti speciali per le zone sismiche*) [8]. In this context, it is evident that the school building stock analyzed in this paper now needs regeneration interventions in order to meet the performance regulatory requirements, in terms of energy and seismicity, and deserves reflections and evaluations to assess alternative scenarios. These scenarios correspond to two opposing intervention paradigms: deep renovation or demolition and reconstruction.

1.2. SCHOOL BUILDING STOCK IN BOLOGNA

The school infrastructure in the city of Bologna follows common national trends in energy and structural performance. In response to post-war demographic expansion in the 1960s and 1970s, the city adopted prefabrication techniques to quickly construct public buildings, including schools. Prefabrication was chosen due to its cost-effectiveness, standardization, and rapid construction times, aligning with modern educational design principles at the time, based on the transformation of the school from an institution to a service. This modern conception of a school as a social service is reflected in the transformation of the building type as well, which shifts from monumental solutions, designed to confer a representational character associated with the institution, to an anonymous architectural space, devoid of any specific architectural character, designed to accommodate a social service, including classrooms, laboratories, and sports spaces (Fig. 1). To distance themselves from the traditional layout based on single-sided classrooms on a common corridor, the new models for schools propose compact floor plans that eliminate the blind spaces that hinder the smooth flow of activities, to enrich the relationships between different educational environments. Thus, open-plan building layouts are realized, resulting from the aggregation of building blocks conceived as unified structural units, which can be subdivided into a wide range of rooms of varying extension to suit different activities, using modular, flexible, and easily movable building components and furniture.

As remarked by Cervellati [9], between 1970 and 1975, Bologna constructed 100 school buildings out of 154 planned, with an additional 51 projects completed between 1975 and 1980, primarily for middle schools. Focusing on middle school buildings in Bologna, today, 60% of them were built between 1940 and 1990, and 70% of them feature partially or entirely prefabricated structures. This distribution reflects a national trend where modular designs were replicated across different locations, with minor adaptations to fit specific sites.

The municipal apparatus changed its technical-administrative organization to realize the school building construction plan for the five years 1970-1975. Most of the projects were prepared by the Municipality's Technical Office, and only some of them were commissioned to external designers and built under the direction of municipal technicians or external parties. To build many schools in a short period of time, the Municipality's Technical Office adopted reference models that were replicated and adapted to the different contexts of the specific building's location, maintaining the architectural

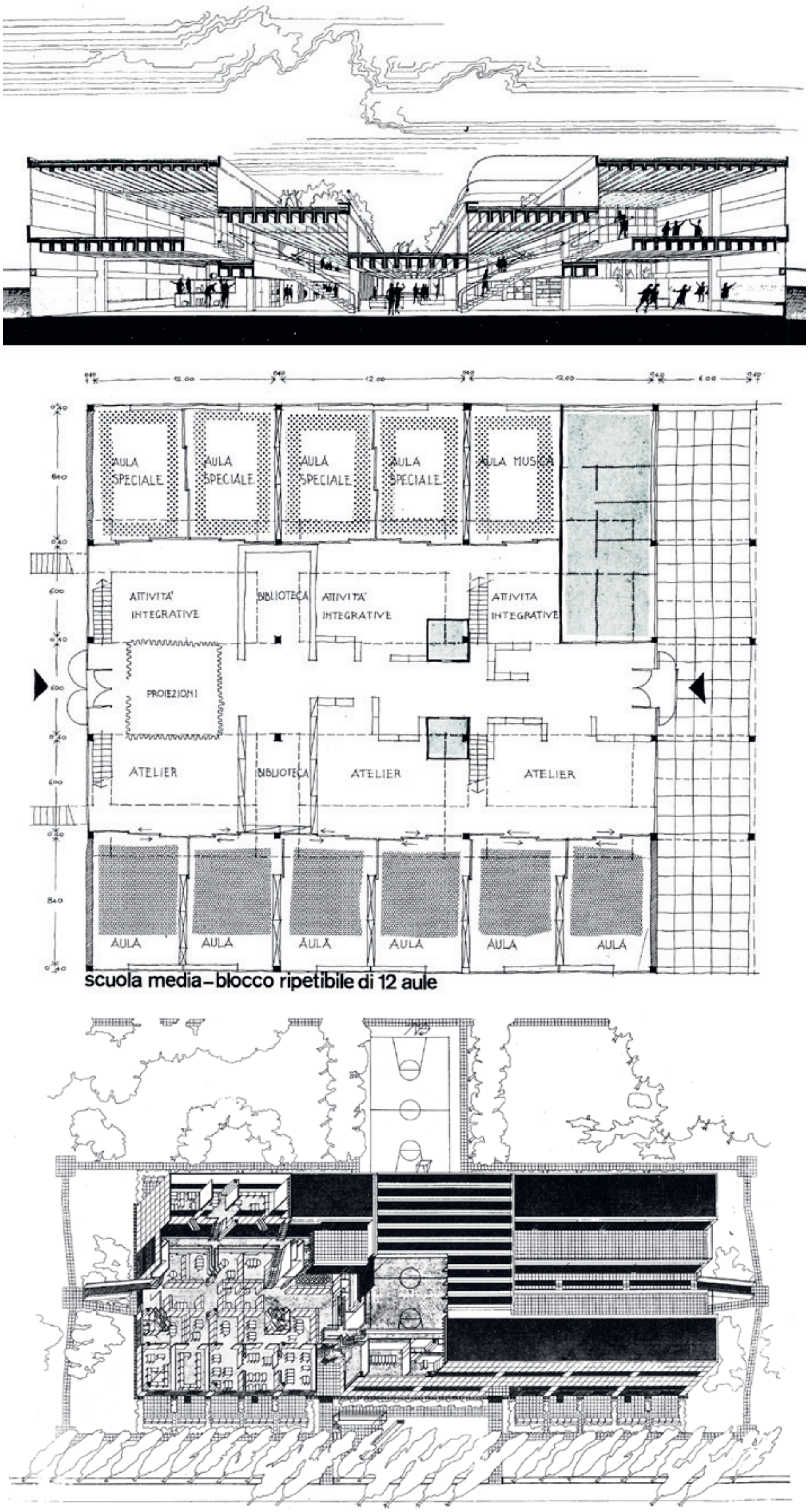

Fig. 1. *From the top to the bottom: schematic cross-section and plan of the internal distribution of the 12 classrooms constituting a repeatable and aggregable block for the Middle School model elaborated by the working group of the Technical Office of the Municipality of Bologna. Source: [9]. Axonometry of the modular scheme resulting from the aggregation of two blocks, for a total of 24 classrooms. Source: [10].*

Fig. 2. *Orthophotos of the Comprehensive Schools I.C. (Istituti Comprensivi) in the Municipality of Bologna made by replicating the same project in five different contexts: (1) I.C. No. 10 "Besta" - San Donato District; (2) I.C. No. 15 "Zappa" – Navile District; (3) I.C. No. 14 "Volta" - Borgo Panigale District; (4) I.C. No. 1 "Dozza" – Reno District; I.C. No. 9 "Guercino" – Savena District. Top right, location of schools in the suburbs of Bologna. Source: Authors, 2025.*

and aesthetic-formal characteristics as well as the technological and construction characteristics.

Among these models, a key example is the Besta School in the San Donato district, built in 1979-80 as part of a series of five identical school complexes (Fig. 2). These structures followed the same functional block layout, using reinforced concrete frames and floor slabs – totally or partially prefabricated – and precast cladding panels. The design adhered to the heliothermic axis (19° tilt to optimize sunlight exposure), reflecting early 20th-century theories on thermal comfort [5]. While this construction model was effective in the past, today it presents severe energy and seismic vulnerabilities, necessitating comprehensive renovation strategies.

In the specific case of the Besta School, unlike the other schools built according to the same reference model, the construction system is mixed and hybridizes prefabricated elements with on-site works. In particular, the inverted T-beams foundations and the multi-storey columns are made of reinforced concrete and cast-in-situ while the inverted T-beams of the primary frame and the secondary TT slab (*copponi*) are precast concrete elements; the prefabricated cladding panels, made by Edilfornaciai S.c.r.l., consist of two layers of concrete interlocking an 8 cm thick insulating layer of polystyrene (density 30 kg/m^3), with an external covering of white washed gravel (total thickness 24 cm), and are anchored to the load-bearing structure by means of metal point fixings using brackets and L-shaped angles (Fig. 3).

This heritage presents a series of critical issues that can be defined as intrinsic, as it was conceived within a regulatory framework that does not regulate, or only marginally regulates, performance requirements, especially those related to energy consumption and seismic vulnerability. However, these buildings are highly representative of the era when industrial prefabrication governed construction processes, which certainly justifies the activation of renovation strategies to prolong the service life of this asset, to preserve the historical-documentary value, and to avoid the significant environmental, economic, and social impacts that the hypothesis of demolition and reconstruction would entail. This reflection is in line with the ongoing debate between the Municipality and some citizens' committees about the demolition and replacement of the school with a new building in the adjacent park, which would impact the green area within which the school is locat-

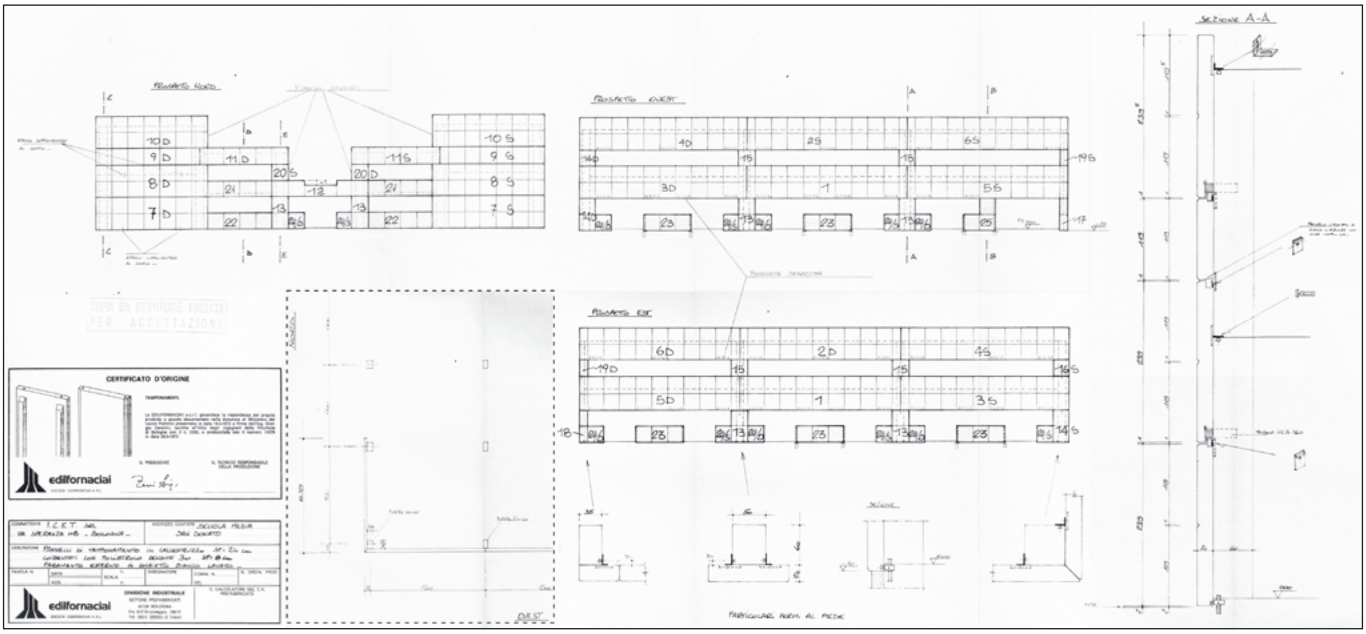

Fig. 3. *Technical drawings of the Besta School project: construction detail of prefabricated exterior cladding panels. Source: Authors, 2025 Re-elaboration after Historical Archives of San Giorgio di Piano (Polo Archivistico Regionale dell'Emilia-Romagna), San Giorgio di Piano, Bologna, 2015.*

ed, reducing the permeable surface and leading to the removal of existing trees (Fig. 4).

To provide a critical base for a possible decision-making process, the present research intends to investigate different intervention scenarios and evaluate and compare the different impacts they have on the environment through the adoption of a rapid assessment method. The scenarios considered share the following objectives: reduction of seismic vulnerability, improvement of environmental comfort, and reduction of energy consumption through enhanced building envelope efficiency. Given the replication of the same project to four other case studies, these evaluations could have a more extensive value on the stock of school buildings having the same technological and construction characteristics.

2. RAPID ASSESSMENT OF RENOVATION SCENARIOS: THE S.C.O.R.E.S. TOOL

Expedited evaluation methods can help end users understand renovation dynamics, allowing them to identify the impacts of different intervention solutions. This improved understanding reduces initial resistance to changes and increases acceptance and appreciation of renovation solutions. Additionally, active participation fosters long-term sustainability measures, spreading awareness of the benefits of energy retrofitting. High initial costs often deter both public and private investors, and the lengthy payback period further exacerbates uncertainty and reluctance among stakeholders. However, a higher upfront investment does not always mean a longer return on investment (ROI). In

Fig. 4. *Current photos of the Besta school. Left: a view of the main front from the dense park, adjacent to the Bologna Fair towers. Source: Authors, 2025. Middle: a view of the main entrance front. Source: Authors, 2025. Right: a view of the interior. Source: https://appaltipnrr.it/appalto-bologna-costruzione-scuola-media-besta/.*

some scenarios, initially more expensive interventions lead to greater annual savings, resulting in faster payback periods [11]. For non-expert users, energy assessment can be complex, involving technical parameters and regulations that are not intuitive. Understanding the economic benefits of investments in energy efficiency requires specific knowledge of actual energy savings. Raising awareness about the environmental impact of buildings and the importance of retrofitting for sustainability requires a detailed understanding of heating, cooling, and building materials. To address these challenges, clear communication and simplified tools are essential. This premise led to the development of S.C.O.R.E.S. (Sustainable Construction or Renovation Easy Scoring), a user-oriented tool that allows for quick comparisons of different intervention scenarios. The tool provides a rapid quantitative assessment, expressed through a numerical score for each intervention strategy, allowing easy comparison between various scenarios. The S.C.O.R.E.S. concept originated in the author's doctoral research on rapid multi-criteria assessment of renovation options [12]. The present implementation was then developed and calibrated using monitoring, design, and cost data from the Pro-GET-onE pilot case [13]. Specifically: (i) the concept and the scoring structure derive from the doctoral framework; (ii) default energy and life-cycle impact benchmarks were parameterized from [13]; and (iii) the scenarios set and indicator rubrics were checked against the pilot outputs to ensure internal consistency across Energy, Environment, and Costs. The tool's consistency was validated by applying it to multiple buildings and analyzing four intervention scenarios over five different timeframes (15-100 years). These analyses were repeated using both actual and statistical primary energy demand values, ensuring consistency and reliability of the results through internal review. Finally, the tool was tested by a sample of potential users, including both experts and non-experts, to evaluate its accessibility for different user categories.

2.1. PROJECT STRATEGIES AND INTERVENTION SCENARIOS

S.C.O.R.E.S. evaluates various renovation scenarios by assigning a numerical score based on key indicators. After entering a few building details, the tool allows users to choose between three priority strategies:

- Energy: Optimize energy efficiency by reducing primary energy demand;
- Environment: Minimize greenhouse gas emissions over the building's life cycle;
- Cost: Minimize life-cycle costs.

The simulation assesses nine core indicators, evenly distributed among energy, environmental, and economic factors. Additionally, three intervention-specific indicators influence the final score based on user needs. The tool ranks different scenarios based on the selected timeframe (15, 25, 50, 75, or 100 years) and chosen strategy (Energy, Environment, Cost).

1) Current State (Baseline Scenario):
   - the building remains unchanged, with no renovation or seismic improvements;
   - this option serves as a reference point for assessing the long-term costs and inefficiencies of inaction.
2) Renovation (Energy Efficiency Only):
   - involves classic energy renovation (e.g., insulation, HVAC system upgrades) without seismic retrofit;
   - reduces operating costs and CO_2 emissions but leaves the building vulnerable to seismic risks.
3) Renovation with Volumetric Additions (Energy and Seismic Retrofit with Exoskeleton):
   - integrates energy renovation with structural reinforcement, using a steel exoskeleton to enhance seismic safety;
   - this approach consolidates and strengthens the building while improving energy efficiency;
   - ensures compliance with modern seismic regulations, providing an optimal balance between sustainability and structural safety;
   - it also allows volumetric façade addition.
4) Demolition and Sustainable nZEB (Near Zero Energy Building) Reconstruction:
   - entails complete demolition and circular reconstruction of a nearly zero-energy, earthquake-resistant building;

- maximizes long-term energy savings, minimizes CO_2 footprint, and provides the highest seismic resilience;
- however, it involves higher initial costs and environmental impacts from material disposal and new construction.

In particular, Scenario 3 simulates the situation where the building would undergo a renovation following the strategy promoted by the European Horizon 2020 Pro-GET-onE project. This system combines seismic retrofit and energy efficiency using a steel exoskeleton, allowing the structural reinforcement and, at the same time, the building envelope refurbishment, as well as the integration of systems. The exoskeleton supports seismic loads, distributes structural stresses, and allows for additional volumetric expansions without altering the primary load-bearing elements. By enclosing the existing building, it minimizes construction waste and disruption for occupants, providing a cost-effective alternative to demolition and reconstruction [13]. Scenario 4 represents a highly sustainable reconstruction strategy, designed to achieve net-zero operational carbon emissions. In this scenario, the existing school building is entirely demolished and replaced with a mass timber structure using Glued Laminated Timber (Glulam) and Cross-Laminated Timber (CLT) components. These materials reduce embodied carbon, improve thermal insulation, and provide earthquake-resistant performance. While the initial investment is higher, the long-term benefits include lower operational costs, improved comfort, and enhanced seismic resilience.

2.2. IMPACT ASSESSMENT AND TOOL IMPLEMENTATION

S.C.O.R.E.S. operates as a spreadsheet-based tool requiring minimal input. Essential parameters include construction period and gross floor area. Based on these, the system assigns a statistical primary energy demand (EP) derived from national certification databases [14]. The tool refines EP estimates based on renovation history or known energy ratings [15, 16]. S.C.O.R.E.S. utilizes a multi-criteria evaluation approach to compare different renovation scenarios based on energy, environmental, and economic performance. This section outlines the methodology used to compute the key indicators, weighting factors, and scoring system. Each scenario is assessed through a set of nine core indicators (energy, environmental, and economic indicators) and three additional indicators illustrated in Table 1. The tool evaluates nine indicators (balanced across energy, environmental,

Category	Indicator	Unit
Energy Indicators	Primary Energy Demand (EP_{gl})	kWh/m²y
	Non-Renewable Primary Energy ($EP_{gl, nren}$)	kWh/m²y
	Share of Renewable Primary Energy	%
Environmental Indicators	Embodied Carbon Emissions	tCO_{2eq}
	Operational Energy Emissions	tCO_{2eq}
	Total Life-cycle Emissions	tCO_{2eq}
Economic Indicators	Initial Investments	€
	Operational Energy Costs	€
	Total Life-cycle Costs	€
Other Specific Indicators	Seismic Safety Level	-
	Need for Temporary Relocation	-
	20% Volume Extension	-

Tab. 1. *Key Indicators calculated by S.C.O.R.E.S.*

and economic pillars) plus three scenario-specific indicators reflecting stakeholder priorities. Each main indicator receives a discrete score from 1 to 4 based on the computed performance.

Strategy weights – Energy, Environment, Costs – are applied as coefficients {0, 1, 2, 3} to emphasize the chosen priority.

$$S = \sum (Ii \times Wi) \tag{1}$$

where:

- S = total scenario score;
- Ii = individual indicator score (ranging from 1 to 4);
- Wi = weighting factor (ranging from 0 to 3, based on user preference).

Other Specific Indicators have been defined for representing specific requirements that the intervention might involve, such as the need for the achievement of seismic retrofit, for the temporary relocation of occupants and services, and for the potential of implementing a volumetric expansion. These indicators are assessed through a numerical score ranging from 1 to 3 assigned by the user, based on the intervention priorities. These additional indicators are not subject to weighting factors like the other categories. If they are absent, their score is set to 0: instead, they function as binary modifiers that either add or do not add to the total score based on whether the criteria are met. These are defined as follows:

- Seismic Safety Level: if an intervention meets seismic requirements, a predefined bonus is added;
- Need for Temporary Relocation: if the scenario requires relocation during renovations, a penalty is applied;
- Volumetric Expansion: if an intervention provides additional usable space, a bonus is applied.

The tool ultimately generates ranked scores for all scenarios, enabling easy comparison (Fig. 5). Additionally, a cumulative cost graph is provided to illustrate projected long-term financial impacts. Users can also access detailed indicator breakdowns and sensitivity analysis results, ensuring transparent decision-making based on quantified performance metrics. The total score, which sums the Energy, Environmental, and Economic Indicators, ranges from 0 to a maximum of 36, obtainable if each of the three indicators is ranked with a maximum score of 4. The total score related to the sum of the Other Specific Indicators, instead, ranges from 0 to a maximum of 9, obtainable if each one of the three indicators is ranked with the maximum score of 3.

S.C.O.R.E.S. is primarily data-driven: most criteria are measured or modeled quantities (e.g., delivered energy, life-cycle GWP, LCC). Each indicator value is mapped to a discrete 1–4 score using published rubrics with thresholds anchored to regulations, benchmarks, or literature, so the translation from performance to score is pre-specified and reproducible. Decision priorities are reflected through small integer strategy weights {0, 1,

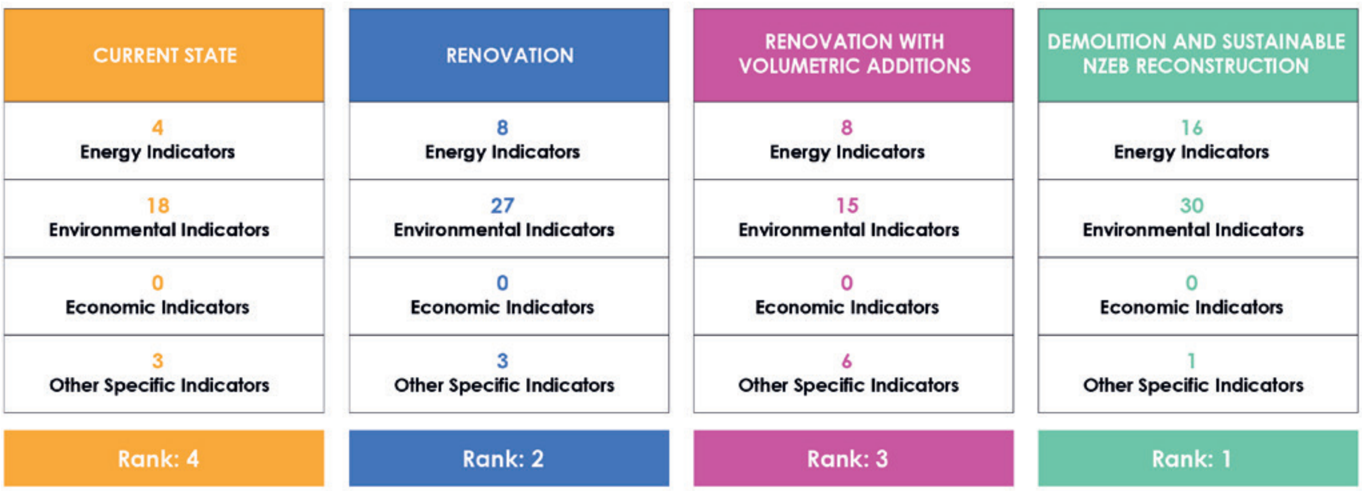

Fig. 5. *Output screenshot related to the results of the S.C.O.R.E.S. tool applied to the Besta School, at 100 years by selecting the Energy strategy. Source: Authors, 2025.*

2, 3} applied to the three pillars (Energy, Environment, Costs); these weights are chosen from a pre-defined set (e.g., Energy-led, Environment-led, Cost-led) and reported explicitly. Three scenario-specific requirements are captured as binary criteria (1 if met, 0 otherwise). The overall score is then a simple weighted sum of the discrete indicator scores plus the binary terms – there are no hidden normalizations or opaque aggregation operators. Consequently, scores are not entirely dependent on the user's subjectivity: judgment enters only in selecting a weight set within {0–3} and, where measurements are unavailable, in applying a documented proxy rubric.

3. THE BESTA SCHOOLS RENOVATION PROJECT AS A CASE STUDY FOR THE IMPLEMENTATION OF S.C.O.R.E.S.

3.1. THE BESTA SCHOOLS RENOVATION PROJECT

As introduced, the Besta Schools in Bologna have been at the center of an urban redevelopment debate. The initial plan proposed by the Municipality of Bologna aimed at demolishing the existing school buildings and rebuilding them within Parco Don Bosco, raising concerns about the loss of green space and tree removal. The controversy centered on the removal of approximately 30 trees, sparking strong opposition from environmental groups and residents [17]. The Municipality responded by committing to a tree replanting initiative, stating that two new trees would be planted for each one removed and that over 80% of the existing trees would be preserved [17]. Public opposition led to months of protests, petitions, and negotiations, culminating in April 2024, when tensions escalated as police intervened to secure the construction site, resulting in confrontations and injuries [17]. However, in July 2024, after continuing pressure from the community, the Municipality revised its plan and announced that the new school would instead be relocated to the Polo Dinamico, where it would share space with the Copernico High School [18]. The revised new school building has been designed to significantly reduce carbon emissions, aligning with Bologna's participation in the "100 Climate-Neutral Cities" initiative [19]. The school would have functioned as a "net-zero energy building", producing more energy than it consumes through renewable sources. Additionally, the new structure meets modern seismic standards, ensuring increased safety for students and staff [19].

3.2. THE ROLE OF S.C.O.R.E.S. IN SUPPORTING TRANSPARENT DECISION-MAKING

Large-scale renovations in public school buildings often generate strong reactions from local communities. Citizens are particularly concerned about changes that affect the urban environment, public green spaces, and school infrastructure. The case of the Besta Schools highlights the complexity of decision-making in public infrastructure projects, where technical, environmental, and social factors must be carefully balanced. In such scenarios, S.C.O.R.E.S. could serve as a support tool, enabling a swift multi-criteria comparison between different intervention strategies. The Besta School case demonstrates how such an assessment tool could have helped in objectively showing the trade-offs between deep renovation, hybrid solutions like Pro-GET-onE, and complete reconstruction. In complex public projects where diverse factors must be communicated effectively, having an accessible and transparent tool can facilitate consensus-building and foster greater public trust in infrastructure decisions. Transparent decision-support tools like S.C.O.R.E.S. can help stakeholders navigate the trade-offs between different intervention strategies. Citizens can be involved in structured workshops and meetings where S.C.O.R.E.S. scenarios are presented and discussed. S.C.O.R.E.S., initially developed for private residential buildings, can be effectively applied to public buildings to enhance citizen awareness of the impacts of different renovation strategies. Policymakers, urban planners, and residents can collectively evaluate the most sustainable and cost-effective intervention strategies using the tool's comparative analysis.

3.3. INPUT DATA AND SIMULATION SETUP

To evaluate the renovation strategies for the Besta School, a series of simulations was conducted using the

S.C.O.R.E.S. tool. The following key inputs were considered (Fig. 6):

- Assessment Periods: simulations were run for 15, 25, 50, 75, and 100 years to assess how results change over time;
- Construction Date: the school was built in the late 1970s, so the 1977-1991 construction period was selected;
- Gross Floor Area: the school covers a total area of 5415 m².
- Energy Performance Data: since no prior renovations or energy certification data were available, the tool calculated a statistical primary energy demand (EP) of 168.1 kWh/m²y and CO_2 emissions of 49.30 $kgCO_2e/m^2y$.

Subsequently, the scores for the specific indicators were assigned: a high score of 3 was given to seismic safety and the possibility of not having to vacate the building during construction, as these aspects are of fundamental importance when evaluating intervention scenarios for a school building; conversely, a low score of 1 was assigned to the 20% volumetric expansion, as it was deemed less critical in this context. The simulation aimed to compare different renovation scenarios based on energy efficiency, life-cycle emissions, and economic feasibility.

3.4. SCENARIO EVALUATION AND KEY FINDINGS

The analysis conducted through the S.C.O.R.E.S. tool allowed for a direct comparison of four intervention scenarios – Current State, Renovation, Renovation with Volumetric Additions, and Demolition and Sustainable nZEB Reconstruction – considering energy demand, greenhouse gas emissions, and cost-effectiveness over different time horizons.

3.4.1. ENERGY AND ENVIRONMENTAL IMPACT ASSESSMENT

The energy and environmental strategies consistently ranked demolition and reconstruction as the most effective intervention over extended periods. This result was

BUILDING DATA	
Project name	**Besta School**
Address	**Via E. Zacconi 11, 40127 - Bologna**
Assessment period (years)	**50**
Construction date	**1977-1991**
Building type	**Other**
Gross area [m²]	**5415**
Has any renovation work already been implemented?	**Yes**
Please specify	**Generator (condensing boiler or heat pump)**
Do you know the energy class?	**No**
Please specify	**B**
Do you know the building EP_{gl}?	**No**
Please specify $EP_{gl, nren}$ [kWh/m²y]	
Please specify $EP_{gl, ren}$ [kWh/m²y]	
Do you know the energy consumption?	**No**
Natural gas [m³/y]	
Electric energy [kWh/y]	
Do you know the energy bill charges?	**No**
Total yearly charges for gas	
Total yearly charges for electricity	

ENERGY PERFORMANCE	
Current state $EP_{gl, nren}$ [kWh/m²y]	Energy class at the current state
168.1	E
Assumed $EP_{gl, nren}$ [kWh/m²y]	Assumed E_p coefficient
168.1	1

EMISSIONS	
[$kgCO_{2eq}/m^2y$]	49.30

ENERGY COSTS	
Total bill charges for energy consumption [€/m²y]	17.16

Fig. 6. *Input screenshot related to the results of the S.C.O.R.E.S. tool applied to the Besta School, at 100 years, by selecting the Energy strategy. Green cells must be filled with free text, orange cells must be filled with multiple-choice text, and magenta cells are automatically calculated by the tool. Source: Authors, 2025.*

primarily due to the nearly-zero operational energy consumption of an nZEB, which significantly outperformed all other scenarios in reducing primary energy demand and carbon emissions.

- Current State: without intervention, the school exhibits an energy demand of 168.1 kWh/m^{2}y and an emissions rate of 49.3 kgCO_2e/m^{2}y. Over a 50-year period, this would result in an accumulated energy demand of approximately 8405 kWh/m^2 and total emissions of 2465 kgCO_2e/m^2, highlighting its substantial environmental footprint;
- Renovation Scenario: implementing a 60% reduction in energy demand through insulation improvements, HVAC upgrades, and more efficient systems lowers energy consumption to 67.2 kWh/m^2·y. While this significantly decreases operational emissions, the embedded carbon footprint from material replacement remains moderate;
- Renovation with Volumetric Additions: this intervention, which involves structural reinforcement through an exoskeleton, achieves a similar energy reduction to the renovation scenario (~60% reduction in energy demand), but with higher embedded emissions due to the additional materials. Over a 50-year period, its total carbon footprint surpasses that of standard renovation;
- Demolition and Sustainable nZEB Reconstruction: despite a high upfront carbon cost from demolition and new material production, this scenario achieves near-zero operational emissions. Over a 100-year timeframe, this results in the lowest cumulative life-cycle emissions, making it the best option for long-term environmental sustainability.

Figures 7 and 8 illustrate the long-term evolution of the Global Warming Potential (GWP) and Life Cycle Costs (LCC) for the four intervention scenarios over different time horizons (15, 25, 50, 75, and 100 years). The GWP chart (Fig. 7) shows that, although the renovation strategies perform well in the short term, the demolition and reconstruction strategy results in the lowest overall carbon footprint over a 100-year period. The current state remains the least sustainable across all horizons. Regarding LCC (Fig. 8), while renovation is the most cost-effective option at 15 and 25 years, the demolition and reconstruction becomes the most advantageous from 50 years onward. Deep renovation with volumetric additions consistently presents higher costs, reflecting the added complexity and material use.

A crucial aspect of building sustainability is its carbon footprint, which is composed of two primary elements. The first is embodied emissions, which refer to the CO_2 emissions produced during the construction process and the manufacturing of building materials. These emissions are released from activities such as the extraction of raw materials, transportation, and assembly of structural components. The second component is

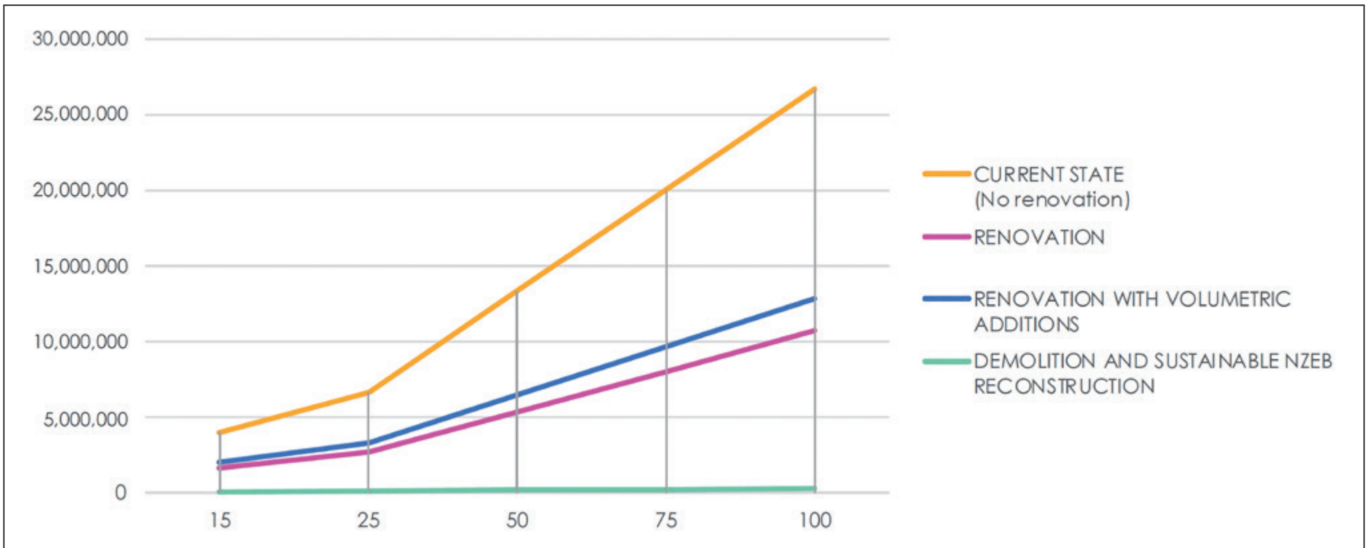

Fig. 7. *Chart of greenhouse gas emissions (kgCO_2e, y-axis) under different time horizons (years, x-axis). Source: Authors, 2025.*

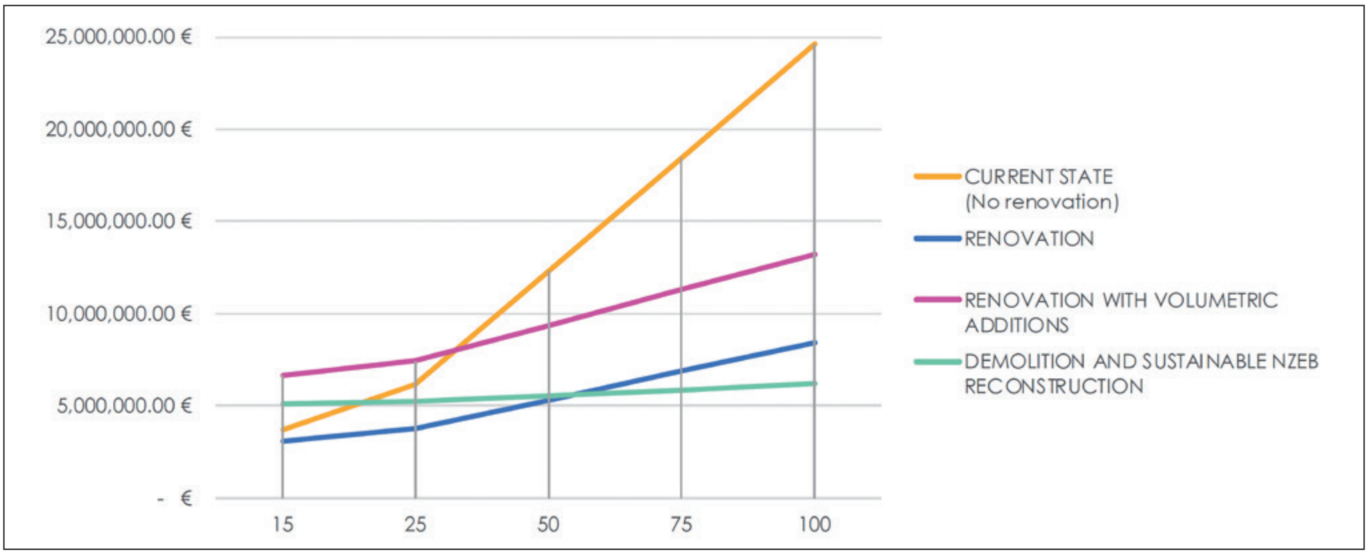

Fig. 8. *Chart of LCC (€, y-axis) under different time horizons (years, x-axis). Source: Authors, 2025.*

operational emissions, which are generated throughout the building's lifetime due to energy consumption. This component includes the emissions associated with heating, cooling, lighting, and other daily operations necessary for the building's functionality. Both factors play a significant role in determining the overall environmental impact of a structure; thus, balancing them effectively is key to achieving long-term sustainability.

- Current State: the worst performer, accumulating 2465 $kgCO_2e/m^2$ over 50 years, as no improvements have been made;
- Renovation: reduces operational emissions to 986 $kgCO_2e/m^2$, offsetting the 4 $kgCO_2e/m^2$ embodied carbon cost;
- Renovation with Volumetric Additions: introduces a higher embodied carbon footprint (11 $kgCO_2e/m^2$) due to the steel exoskeleton, but achieves significant operational carbon savings, lowering the total emissions to 845.2 $kgCO_2e/m^2$;
- Demolition and Reconstruction: reaches an operational CO_2 footprint close to zero, keeping total emissions at only 25 $kgCO_2e/m^2$—a ≈99% reduction compared to the Current State.

Relative to S0 (current state), total life-cycle greenhouse-gas emissions over 50 years change as follows: renovation, −59.8%; renovation with volumetric additions, −51.5%; and demolition and sustainable nZEB reconstruction, −98.8%. Considering operational emis-

Scenario	Embodied Emissions [$kgCO_{2eq}$]	Operational Emissions [$kgCO_{2eq}$, 50 years]	Total Emissions [$kgCO_{2eq}$, 50 years]
CURRENT STATE (No renovation)	0	13,347,975	13,347,975
RENOVATION	21,660	5,339,190	5,360,850
RENOVATION WITH VOLUMETRIC ADDITIONS	71,478	6,407,028	6,478,506
DEMOLITION AND SUSTAINABLE NZEB RECONSTRUCTION	32,490	129,960	162,450

Tab. 2. *Total greenhouse gas emissions ($kgCO_2eq$) over a 50-year period.*

sions only, the reductions vs S0 are −60.0%, −52.0%, and −99.0%, respectively. Percentages for embodied emissions are not reported because S0 has no embodied component. These findings confirm that, while renovation strategies provide moderate reductions, full reconstruction results in the lowest total emissions in a long-term perspective.

A cross-temporal analysis of primary energy demand reveals substantial differences in performance across the four scenarios. The current state results in the highest cumulative consumption, with both renovation and renovation with volumetric additions reducing energy use by over 50% compared to the baseline. However, their performance remains constant over time, showing no further gains beyond the initial intervention. In contrast, demolition and reconstruction limit total demand to only 11.8 kWh/m^2·y, confirming the effectiveness of high-efficiency building envelopes and the integration of renewable energy sources. These energy trends are directly reflected in the GWP.

3.4.2. COST STRATEGY EVALUATION AND ECONOMIC VIABILITY

The economic viability of each scenario varied significantly depending on the selected evaluation timeframe. The analysis of LCC further supports the need for long-term thinking. While renovation is the most economically advantageous option in the short term (€ 3.7 million at 15 years), this benefit diminishes over time. At 100 years, its cumulative cost reaches € 8.5 million, more than that of demolition and reconstruction (€ 6.1 million), which offers far superior environmental and energy performance. The current state incurs the highest cost across all time horizons, reaching € 24.6 million at 100 years, primarily due to high and constant operational energy expenses. Interestingly, renovation with volumetric additions, despite its potential for increasing usable area, proves to be the least efficient strategy from a financial perspective, exceeding € 9.3 million even at 50 years and remaining above that level throughout the whole analysis period.

These results emphasize a key insight: the apparent cost-effectiveness of minimal interventions fades over time, especially when environmental externalities and energy price volatility are considered. Demolition and reconstruction, though initially more expensive, becomes increasingly competitive as the analysis horizon extends – suggesting that long-term investment strategies should account for performance trajectories rather than static comparisons. The strong alignment between energy savings, emission reductions, and cost stabilization reinforces the importance of integrated assessment tools like S.C.O.R.E.S. to support truly sustainable urban regeneration choices.

In the short term (up to 15 years), renovation was the most cost-effective strategy, achieving a score of 37 points, followed by demolition and reconstruction, current state, and renovation with volumetric additions (Fig. 9). However, beyond 25 years, the demolition and reconstruction scenario became the most advantageous due to its long-term cost savings from energy efficiency and lower operational costs.

The break-even points for different scenarios were identified as follows:

- Renovation became more cost-effective than the current state after 12 years due to lower energy expenses;
- Demolition and reconstruction achieved cost parity after 22 years, reflecting the long-term benefits of an nZEB design;
- Renovation with volumetric additions required approximately 26 years to justify the additional structural investments.

The cumulative cost analysis (Tab. 3) further emphasizes these trends, showing that while renovation remains the most economical option up to 55 years, the demolition and reconstruction strategy ultimately results in the lowest total life-cycle costs over 100 years. This trend confirms findings from previous life-cycle cost assessments (LCCA), which indicate that deep renovations and new constructions provide the highest return on investment when evaluated over extended timeframes.

Economic feasibility is crucial in school renovation decisions, assessed through a life-cycle cost analysis considering initial investment, energy savings, mainte-

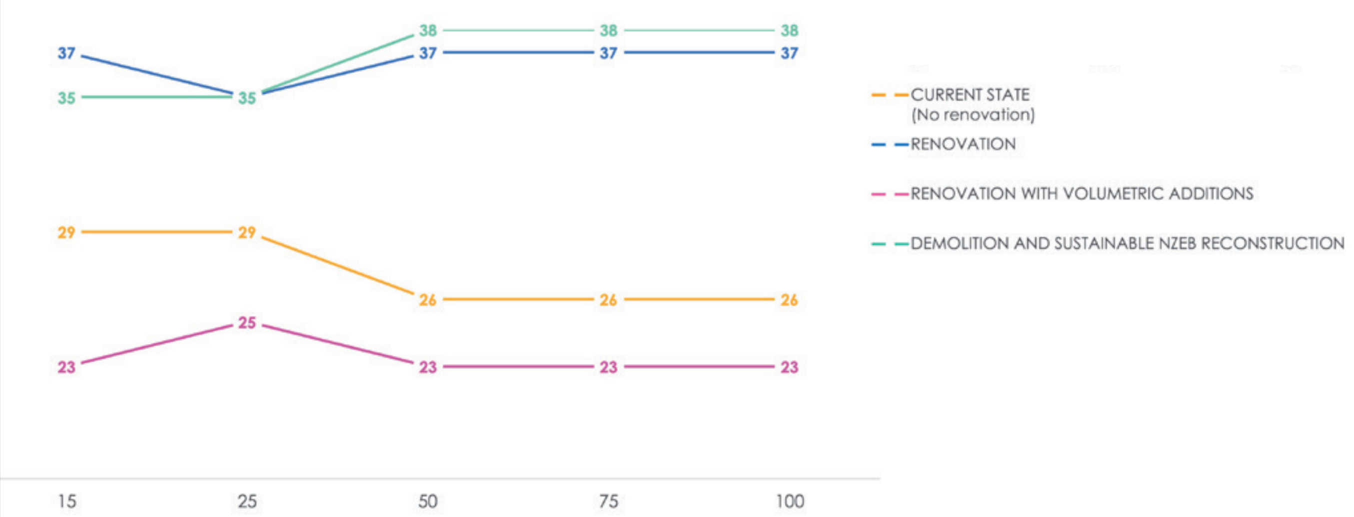

Fig. 9. *Chart of final scores (y-axis) according to the Cost strategy for a calculation period of 15, 25, 50, 75, and 100 years. Source: Authors, 2025.*

nance costs, and payback periods. While higher upfront costs may seem prohibitive, energy-efficient renovations and nZEB construction reduce long-term operational expenses. Lower maintenance needs further enhance financial viability. The payback period determines how quickly the cost savings offset the initial investment, guiding policymakers toward cost-effective and sustainable solutions.

In the short term (15 years), renovation proves to be the most cost-effective solution. In contrast, both renovation with volumetric additions and demolition and reconstruction require higher initial investments, thereby delaying the realization of their financial benefits. Relative to S0, cumulative life-cycle cost at 15 years is −15.8% for renovation, +80.8% for renovation with volumetric additions, and +38.6% for demolition and sustainable nZEB reconstruction. Over the mid-term (25-50 years), renovation with volumetric additions becomes more advantageous than renovation alone, as its structural improvements and greater energy efficiency lead to long-term savings. Simultaneously, demolition and reconstruction gradually approach cost parity with deep renovation strategies. In the long run (75-100 years), demolition and reconstruction emerge as the most financially sustainable options. Thanks to minimal operational costs, it outperforms renovation strategies, which, over 100 years, accumulate significantly higher expenses due to continued energy consumption and maintenance requirements. This behavior confirms a common trend in life-cycle cost assessments: renovation is the preferable option for short-to-medium-term investments, as it provides immediate energy savings, a faster return on in-

Scenario	Initial Investments	Cumulative Cost at 15 years	Cumulative Cost at 15 years
CURRENT STATE (No renovation)	- €	3,691,676.25 €	3,691,676.25 €
RENOVATION	2,166,000.00 €	943,834.50 €	3,109,834.50 €
RENOVATION WITH VOLUMETRIC ADDITIONS	5,523,300.00 €	1,152,095.40 €	6,675,395.40 €
DEMOLITION AND SUSTAINABLE NZEB RECONSTRUCTION	4,927,650.00 €	190,066.50 €	5,117,716.50 €

Tab. 3. *Cumulative costs over different time horizons.*

vestment, and lower initial costs. However, when considering long-term sustainability goals, full reconstruction proves to be the most effective choice. Despite its higher upfront investment, it ensures near-zero operational energy costs, enhanced seismic resilience, and reduced maintenance expenses over time, making it the most sustainable solution in the long run. These results align with the trends illustrated, confirming the dynamic nature of sustainability assessments over extended timeframes.

3.4.3. DISCUSSION OF THE SCENARIO ANALYSIS

The Besta School case study highlights the complexity of striking a balance between short-term economic feasibility and long-term sustainability in public infrastructure projects. The comparisons between renovation, renovation with volumetric additions, and demolition and reconstruction reveal how different intervention strategies impact energy efficiency, environmental footprint, and life-cycle costs over time. Renovation and volumetric addition emerge as practical solutions in the short-to-medium term, primarily due to lower initial costs, quicker implementation, and minimal disruption to school operations. These interventions improve energy performance, seismic resilience, and comfort levels while allowing the building to remain functional during upgrades. However, the economic and environmental advantages of renovation tend to diminish over time as energy savings plateau and maintenance requirements increase. In contrast, demolition and reconstruction, despite higher upfront investment and embodied carbon emissions, become progressively more advantageous over a longer time horizon. The near-zero energy demand of an nZEB building significantly reduces operational costs, and its seismic resilience minimizes future retrofitting needs. Over a 100-year period, these factors lead to substantial economic and environmental benefits, making reconstruction the most effective long-term strategy. These findings emphasize the importance of data-driven decision-making in urban planning. Quantitative tools like S.C.O.R.E.S. can help policymakers, engineers, and stakeholders navigate complex trade-offs by providing clear, comparative assessments of different scenarios. By integrating energy consumption data, carbon emissions analysis, and cost projections, S.C.O.R.E.S. ensures that renovation choices align with both short-term financial constraints and long-term sustainability objectives. Beyond technical evaluation, such tools could be valuable in public engagement processes, where community concerns and stakeholder input can significantly influence project acceptance. The Besta School case highlights how transparent, evidence-based assessments can bridge the gap between technical experts and the public, enabling a more informed, participatory approach to renovation planning. By making complex sustainability metrics accessible, decision-support tools like S.C.O.R.E.S. could enhance trust, acceptance, and collaboration in large-scale urban redevelopment projects.

4. URBAN TREE RESTORATION AND THE ROLE OF BIOBASED MATERIALS IN SUSTAINABLE CONSTRUCTION

Urban redevelopment projects involve complex trade-offs between energy efficiency, environmental impact, material sustainability, and community needs. As seen in Section 3, long-term planning is essential for minimizing impacts and ensuring resilient, future-proof buildings. However, the preservation of green areas and mature trees adds an additional layer of complexity. Tree removal and replanting raise questions related to carbon sequestration, biodiversity, and microclimatic regulation. Urban trees mitigate the urban heat island (UHI) effect, enhance air quality, and serve as carbon sinks. At the same time, using biobased construction materials – particularly, engineered timber – can help retain part of the carbon stored in trees by incorporating it into long-lasting structures. This section explores the role of urban trees in climate mitigation, the carbon performance of timber construction, and the potential of replanting as a compensatory measure.

Building on the multi-criteria results, the discussion interprets the scenario ordering within the same scoring frame: discrete 1–4 indicator scores combined with integer weight sets {0–3} for Energy, Environment, and Costs, with three scenario-specific binary requirements. The preservation and restoration of urban trees influence operational performance by moderating summer loads and urban heat exposure through shade and evapotranspiration, while generating establishment and maintenance cost streams over the analysis horizon. Adoption of biobased materials – particularly, engineered timber – affects embodied impacts and end-of-life balances via biogenic carbon accounting consistent with EN 15804, and introduces performance constraints (durability, moisture management, fire safety) that shape replacement cycles and life-cycle costs. With balanced priorities, the leading option reflects larger reductions in delivered energy and GWP relative to its cost profile; under cost-led priorities or short time horizons, trade-offs can reweight the ordering. The ensuing discussion translates these mechanisms into actionable guidance, indicating when tree strategies and biobased assemblies reinforce the preferred option and when alternative priorities may justify a different choice.

4.1. THE ROLE OF URBAN TREES IN CLIMATE REGULATION AND CARBON SEQUESTRATION

Urban trees play a crucial role in mitigating the UHI effect, sequestering carbon, and supporting biodiversity. Their cooling effect is particularly relevant in densely built environments. Research has shown that urban tree cover can lower land surface temperatures (LST) by 0–4°C in Southern European cities and by 8–12°C in Central European cities, significantly reducing heat stress during summer and extreme heat events [20]. This reduction contributes to lower cooling energy demand in buildings, improving overall urban resilience. Mature trees serve as highly effective carbon sinks, accumulating substantial biomass over decades. When a mature tree is removed, much of its stored carbon is re-released into the atmosphere, making replacement through replanting a long-term rather than an immediate solution. Reforested areas require several decades to restore the carbon stock of established forests, as tree growth rates and sequestration efficiency depend on species selection, environmental conditions, and forest management strategies. While newly planted trees contribute to carbon capture, their ability to match the sequestration capacity of mature specimens develops gradually over time, emphasizing the importance of conserving existing trees whenever possible [21]. Given these factors, preserving existing mature urban trees is important, particularly in cities where replanting efforts often face additional challenges such as limited root space, pollution, and soil compaction, which slow growth and reduce survival rates.

4.2. BIOGENIC CARBON, STRUCTURAL TIMBER, AND THE ROLE OF GLULAM IN SUSTAINABLE CONSTRUCTION

Structural timber materials, particularly CLT and Glulam, offer an alternative to high-emission materials like concrete and steel while simultaneously storing biogenic carbon. However, the effectiveness of timber as a long-term carbon sink depends on accurate LCA methodologies. Biogenic carbon refers to the CO_2 absorbed by trees during photosynthesis and stored in wood fiber, meaning that timber materials function as temporary carbon reservoirs. However, this benefit is contingent on forest management practices, the material's lifespan, and its end-of-life date. If timber remains in use for decades in buildings, it delays carbon re-emissions, but if wood waste is incinerated or decomposes, most of the sequestered carbon is released back into the atmosphere [22]. In fact, assuming biogenic carbon neutrality in traditional LCA models oversimplifies the reality of carbon sequestration and release. The timing of emissions plays a crucial role in evaluating the climate impact of wood-based materials. Traditional LCA approaches often assume that biogenic carbon is emitted at harvest, ignoring the delayed release that occurs when wood is used in long-lasting structures [23]. The EN 15804 updates introduce a stricter framework for accounting for biogenic carbon flows. Previously, LCAs often credited timber with its full carbon sequestration potential upfront, ignoring the possibility of carbon re-release at end-of-life. The new methodology requires tracking carbon dynamics throughout all life-cycle stages, ensuring that carbon emissions from disposal processes – such as combustion, decomposition, or recycling – are fully considered. This aspect represents a significant shift in sustainability assessments, preventing overestimation of timber's climate benefits and promoting more accurate comparisons between biobased and conventional materials [24]. One cubic meter of CLT stores between 700 and 900 kg of CO_2, according to the wood species and manufacturing process [25]. Glulam offers similar benefits but with greater structural flexibility, making it ideal for long-span applications and seismic-resistant designs. The durability of Glulam and CLT is a crucial factor in their carbon impact: the longer these materials remain in use, the more effective they are in preventing carbon re-release. This fact highlights the importance of circular economy strategies, where timber components are repurposed or reused at the end of a building's life cycle, further extending their carbon storage potential. However, the substitution effect is equally important in evaluating the climate benefits of timber. The extent to which timber construction reduces carbon emissions depends on multiple factors, including the materials it replaces, the life cycle assessment approach used, and the timing of biogenic carbon sequestration. Studies indicate that substituting timber for high-emission materials, such as concrete, can lead to substantial reductions in embodied carbon, although exact figures vary depending on the methodology and system boundaries [22]. Sustainable timber sourcing, therefore, ensures that biogenic carbon storage translates into real climate benefits. These studies also indicate that newly planted trees require decades to match the sequestration potential of the mature trees, meaning that the climate benefits of reforestation lag the immediate carbon loss from tree removal. In this context, integrating engineered timber solutions like CLT and Glulam into the new design could provide a partial mitigation strategy, ensuring that some of the CO_2 stored in the removed trees remains locked within the built environment rather than being fully re-emitted. The redevelopment of the Besta Schools in Bologna offers an opportunity to apply these principles in urban planning, since the accurate biogenic carbon assessment could help the Municipality's commitment to urban reforestation.

The Municipality of Bologna has integrated reforestation policies into its urban planning framework, requiring that for every tree removed, at least two must be planted [26]. This regulation reflects a commitment to maintaining and expanding urban greenery over time, reinforcing the city's strategy for ecological compensation and sustainability. However, while tree planting contributes to long-term carbon storage, the timeline for effective sequestration varies according to the species, environmental conditions, and maintenance practices. This variability highlights the need for complementary mitigation strategies in urban regeneration. Sustainable construction materials, in particular engineered timber solutions such as CLT and Glulam, offer an opportunity to retain a portion of the carbon stored in removed trees within the built environment rather than releasing it back into the atmosphere. When sourced from responsibly managed forests and incorporated into well-designed structures, these materials contribute to lowering the embodied carbon of buildings while promoting a circular economy. The Municipality of Bologna's commitment to urban greening provides a valuable model, but its effectiveness will ultimately depend on careful implementation, long-term monitoring, and continued investment in sustainable urban forestry, construction practices, and end-of-life scenarios.

5. CONCLUSIONS AND FUTURE DIRECTIONS

The case of the Besta Schools exemplifies the complexity of urban planning, where economic feasibility, environmental impact, and social perception must be carefully balanced. Decision-making in such projects requires a holistic assessment that considers not only financial and technical aspects but also the broader implications for sustainability, user experience, and public engagement. Urban green spaces play a critical role in mitigating the UHI effect, enhancing biodiversity, and sequestering carbon, making tree removal and replanting particularly sensitive issues in redevelopment processes. While municipal policies (e.g., Bologna's Municipality's requirement to plant two trees for every one removed) aim to compensate for ecological losses, their effectiveness depends on long-term growth conditions and carbon sequestration dynamics. A key aspect of evaluating different intervention strategies is LCA, which enables a long-term perspective on carbon emissions, operational efficiency, and material sustainability. Tools like S.C.O.R.E.S. facilitate these evaluations by providing a streamlined, multi-criteria approach that incorporates energy performance, financial viability, urban reforestation, and social acceptance. By making complex sustainability trade-offs more accessible, these tools not only support policymakers and technical experts but also enhance transparency for end-users, fostering greater public participation in planning decisions. Based on an expeditive assessment of several intervention scenarios considering different service life periods, this kind of tool contributes to increasing awareness of users involved in the renovation process, which should nevertheless assume ethical principles for responsible construction as a priority. One significant factor in sustainable construction is the role of biogenic carbon, stored in trees and subsequently in timber-based materials such as CLT and Glulam. Unlike fossil-based emissions, biogenic carbon follows a shorter sequestration cycle, with its long-term retention dependent on responsible forestry, material longevity, and end-of-life strategies. The recent EN 15804 updates refine how biogenic carbon is accounted for in LCA, ensuring that sequestration, emissions, and material reuse are properly tracked. Integrating such advanced carbon accounting within S.C.O.R.E.S. could further enhance its ability to assess the full environmental trade-offs of different redevelopment scenarios. The Besta Schools case highlights the delayed benefits of tree replanting compared to the immediate loss of mature trees, reinforcing the need for accurate biogenic carbon assessments. Incorporating engineered timber solutions into redevelopment projects could provide a partial mitigation strategy, ensuring that some of the CO_2 stored in removed trees remains within the built environment rather than being immediately released. Looking ahead, further refinement of S.C.O.R.E.S. is necessary to enhance its applicability and modeling capabilities for schools, hospitals, and public buildings and to improve its ability to capture the unique sustainability challenges of different urban environments. Additionally, integrating more detailed biodiversity, urban heat regulation, and long-term sequestration metrics could refine its predictive capacity. Enhancing its user-friendly visualization tools could also strengthen its role as a public engagement instrument, ensuring that sustainability considerations are accessible for non-expert audiences. Ultimately, the findings of this study highlight that no single intervention strategy is universally optimal. Instead, the choice between renovation, hybrid solutions, or complete reconstruction depends on the weight assigned to economic, environmental, and social factors. By integrating quantitative decision-support tools, cities can develop more informed, inclusive, and sustainable urban redevelopment policies, ensuring that projects align with both short-term constraints and long-term climate resilience goals.

Authors contribution

Conceptualization and methodology, L.D. and A.F.; analysis, investigation, and validation, L.D., C.M. and A.C.B.; data curation and visualization, L.D. and C.M.; writing original draft preparation, L.D., C.M. and A.C.B.; writing-review and editing, A.F.; supervision, C.M. and A.F.

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