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Comparative LCA Scenarios for Urban Regeneration of Residential Building Stock. Application to an Existing High-density Urban Block in Bologna

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ABSTRACT

The construction sector and the existing building stock are responsible for high environmental impacts. Effective measures for urban sustainable regeneration and reducing the impact of urban areas must address the use of circular solutions to increase the rate of materials reused and reusable and minimise raw materials usage and waste production. Also, nearly zero energy buildings (NZEBs) using only renewable energy sources (RES) without fossil fuels are essential to achieve the decarbonisation target proposed by the European Union by 2050. The comparison of three intervention scenarios, reconstruction (R), deep renovation (DR) and conservation (C), in three different periods (10, 30, and 60 years) using the Life Cycle Assessment method allows for the estimation of their environmental impact in terms of Global Warming Potential and Primary Energy. The experimental application to an existing urban block in the first urban periphery of Bologna (Italy) provides interesting results. In this case, DR is not the most cost-effective in the long term, but the R is the most successful. Further simulations on other existing urban blocks are necessary to extend the results and obtain valuable data to integrate into georeferenced maps used as decision-support tools by local actors to boost the climate neutrality transition.

1. Introduction

The greenhouse gas (GHG) emissions at the global level accounted for 48.5 $GtCO_2e$ in 2020 [1], and the 2022 and 2023 UNEP (United Nations Environment Programme) reports stated that this trend is constantly growing [2]. As long as emissions are continuously balanced by raising the shares of carbon sequestration and removal, GHG emissions are not expected to decrease [3]. The reference organisations for the distribution of accurate climate change data, such as the Intergovernmental Panel on Climate Change (IPCC) and UNEP, agree that stronger strategies must be implemented to support the sustainable development of the built environment and keep the rise in global temperature within the threshold set by the 2015 Paris Agreement (global warming below 1.5 °C) [4]. During the last years, the European Union (EU) launched the European Green Deal in 2019 [5], the new Circular Economy Action Plan (CEAP) in 2020 [6], the legislative package "Fit for 55" in 2021 [7], and a deep revision of the energy regulation (2023) [8]. All these instruments are essential for meeting the decarbonisation target of the building stock by 2050.

The existing EU building stock is responsible for 46% of greenhouse gas (GHG) emissions from the whole-life cycle assessment (comprising indirect emissions from generating heat and power, and embodied carbon), and 40% of the EU's total energy consumption [9]. The first codes about buildings' energy performance entered into force in the 1970s, when thermal insulation standards were first introduced in Europe. 50% of the EU building stock was constructed before 1970, and 75% is energy inefficient according to current regulations [10]. Also, 85–95% of buildings will still be there by 2050; therefore, the existing ones will constitute a significant part compared to the new ones, and they employ outdated technology and inefficient appliances, relying on fossil fuels for heating and cooling [10]. Renovation interventions on the building stock are essential to improve energy performance and reduce consumption, as 54% of final energy consumption (FEC) is used for heating and cooling [10]. However, energy renovation interventions do not exploit all the energy savings potential, as the most common usually are minor renovations concerning the replacement of existing boilers with

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highly efficient ones, and moderate renovations, as insulating interventions of the building envelope, accounted only for 10% [7]. This situation depends on territorial/national aspects related to the governance, local cultures, and traditions, as well as on the consistency of the building stock in terms of use, age, construction techniques, state of conservation, and climatic and economic conditions. In the context of the EU Building Stock Observatory (BSO), the European Commission Recommendation on Building Renovation (EU) 2019/786 defined the following renovation depths according to the energy savings: light (energy savings less than 30%), medium (energy savings between 30% and 60%), and deep (energy savings over 60%). Deep renovation must address both energy and GHG efficiency [11].

The most recent available data (2012–2016) on building renovations in Europe show that energy renovation interventions made up 12.3% of the floor area of residential buildings and 9.5% of non-residential (private and public) buildings. These figures are much lower when we focus on deep renovations: 0.2% for residential buildings and 0.3% for non-residential (private and public) ones [12]. Considering the current barriers to intervention effectiveness – such as that they only affect single dwellings rather than the whole building, the challenges associated with obtaining financial incentives, etc. – the actual renovation rates may be slightly lower [13]. According to these estimates, Italy's renovation rate for residential and non-residential buildings would need to double the existing one of 1.6% of floor area to accomplish the reduction targets set by the EU between 2030 and 2050 [13].

In this context, it is urgent to identify and implement feasible strategies for urban regeneration, including building stock renovation and demolition with reconstruction. The urban areas are responsible for significant environmental impacts, and as of 2007, the urban world population outnumbered the rural population [14]. In 2018, 55% of the population lived in urban areas [15]. Urban areas occupy a very small part of the earth's surface (1–3%), and it is expected that by 2050, they will consume more than 75% of natural resources, produce 50% of global waste and more than 60% of GHG emissions [16]. Several studies [17,18] on cities demonstrated that few big cities are responsible for the most significant environmental impact, so identifying and applying priority actions in urban areas can undoubtedly boost the change.

The Life Cycle Assessment (LCA) methodology for the construction sector [19,20] and Level(s), the European framework for sustainable buildings [21], are the primary tools to implement the strategy for urban regeneration. The application of LCA to buildings allows for obtaining their environmental impact within their life cycle not only in terms of energy but also in terms of GHG emissions by measuring the Global Warming Potential (GWP) indicator [$kgCO_2e$] and the Primary Energy (PE) [MJ] [22]. During recent years, the application of LCA to buildings has progressively shifted the focus to embodied carbon (EC) and embodied energy (EE), as the carbon or energy referring to LCA phases A1–A5, B1–B5 and C1–C4, not depending on the use (operational phases, B6 and B7) [23]. Also, the interest in applying LCA at a larger scale (district, neighbourhood) has grown [24]. However, LCA to buildings and large-scale applications shows a wide variety of data and assumptions, making it difficult to compare results, hampering the definition of benchmarks as environmental performance classes, both at the building and the district/urban block scale [25,26,27]. No agreed methodology proposes defined indicators according to the goal, scope, or system boundaries. This criticality is further accentuated by the specificities of the location that influence the result, whereby sustainable design solutions in one country may not necessarily be so in another. Despite these limitations, the LCA is considered a valuable instrument to evaluate the environmental sustainability of the building stock, and large-scale applications can provide representative figures to be extended to similar building categories, urban clusters, and even to national territory and used to feed decision-support tools [28]. The 'top-down' and 'bottom/up' approaches identified for energy analyses can be extended to the whole-life carbon assessment to simulate environmental performance [29]. In the 'bottom-up' approach, the method of archetypes consists of identifying some building stock's representative models whose environmental impacts are calculated through the LCA. The resulting impacts are extended using these conceptual models (archetypes) to define a baseline, suppose specific renovation scenarios, and assess their benefit by comparing the baseline with different simulations [30].

2. Methods

This paper presents the methodology for comparing three different intervention scenarios in terms of environmental impact using the following indicators: Global Warming Potential (GWP – $kgCO_2e$) and Primary Energy (PE – MJ). The procedure is based on the Life Cycle Assessment (LCA) applied to an existing urban block in Bologna (Italy). Also, this study is included in a broader research aimed at testing the regeneration paradigm "Reconstruction for Regeneration" (R4R) elaborated during a few doctoral researches and master thesis from 2019 to 2024 at the Department of Architecture at the University of Bologna. The R4R strategy is addressed to the housing stock of the second half of the 20th century, constructed during maximum expansion after World War II (WWII) in Italy. The interest is focused on residential use, as it consists of the majority of the existing stock, which does not respect the current standards in terms of energy efficiency and may be suitable both for deep renovation and reconstruction with high transformative potential within the national territory and no restrictions as of the protection of cultural heritage [31].

The methodology envisages the following phases:

(2.1) Structuring the information database and urban fabric's characterisation: this phase is articulated in many sub-phases. The first consists of organising a geodatabase of the existing residential building stock in Bologna, mainly constructed from 1949 to 1965, and making it accessible through georeferenced maps. This period is the most representative of the city, following the consultation of archival sources and documents [32,33], as well as statistical data from the last census (2011) of the housing and population [34]. The data collected and included in georeferenced maps concern association key information, metric/dimensional data, building data, construction data, potential inhabitants, and commercial/real-estate data [31]. The main outputs of the other sub-phases are the recognition of eight urban clusters (a–i) and seven building archetypes (1–7) as a result of a GIS-based urban mapping:

- (a) low-rise mid-compact buildings (1–3 floors), (b) low-rise compact buildings (1–3 floors), (c–d) mid-rise mid-compact buildings (3–5 floors), (e) mid-rise compact buildings (3–5 floors), (f) mid-rise high-compact buildings (3–5 floors), (g) high-rise compact buildings (more than 6 floors), (h) high-rise spacious buildings (more than 6 floors), and (i) low-rise isolated buildings (1–3 floors);
- (1) high-rise high-compact buildings with multi-family row (or closed row) buildings, (2) mid-rise high-compact buildings with multi-family row (or closed row) buildings, (3) mid-rise compact buildings with multi-family row (or closed row) buildings, (4) mid-rise compact buildings with multi-family detached buildings, (5) mid-rise mid-compact buildings with multi-family row (or closed row) buildings, (6) mid-rise low-compact buildings with multi-family row (or closed row) buildings, (7) low-rise low-compact buildings with multi-family detached buildings) [35,31].

Urban clusters come from detailed and accurate density analyses using the 'Spacemate' chart [36], which was applied to 210 urban blocks in the first urban periphery. They were identified in compliance with the categories of the original 'Spacemate' chart and adapted to the Bologna context. In this case, the original clusters (c) and (d) were merged into a unique group, showing that mid-rise buildings in the first peripheries are mostly mid-compact without open spaces. The archetypes, intended as conceptual buildings/buildings category, are identified after analysing a sub-cluster of fifty-five urban blocks (of the 210) belonging to all the urban clusters (a–i). They are the primary reference for extending the results from this sample (55) to the larger one (210), representing the urban periphery.

(2.2) Application to an existing urban block located in the municipal territory of the city of Bologna: this phase is not intended as a real implementation but as an experimental application to a real case to have first results in a preliminary phase before the intervention, and may support the decision by comparing the expected results with the real ones.

The analysed urban block is located outside of the eight urban clusters, referring to archetype "(1) high-rise extremely compact buildings with multi-family row (or closed row) buildings", with the following characteristics: more than six storeys high, no prevailing type of roof (equally alternating flat roof and pitched one), with underground floor and mixed-use ground floor (with commercial and service activities), and reinforced concrete or mixed masonry and reinforced concrete as prevailing vertical load-bearing structures, high population density (PD > 0.08 inhabitants/m^2), Floor Space Index (FSI) > 2 and Ground Space Index (GSI) > 0.5.

Population density (PD) [inhabitants/m^2] = potential inhabitants/ territorial area;

Floor Space Index (FSI) [-] = Σ (gross floor area)$_i$ / territorial area;

Gross floor area (GFA) [m^2] = building footprint · number of floors;

Ground Space Index (GSI) [-] = Σ (building footprint)$_i$ / territorial area, and i = ith building in the urban block.

The urban block is located in the neighbourhood "San Donato" in the North-East part of the city, outside of the historic centre, and it belongs to "Parts of the city to regenerate" according to Action 1.1c included in the general urban plan (Piano Urbanistico Generale – PUG) [37]. It is identified with the univocal code 279 (Fig. 1).

Block 279 covers a rectangular area of 1.46 ha, and the principal axes are oriented in North-East and South-West directions. An in-depth study at the urban block scale via on-site and virtual surveys is performed to preliminarily assess the liveability and environmental quality according to the following indicators [38]: (i) the presence of services and shops (community-serving retail, food shops, community facilities, management, and hospitality activities) located inside and outside (ped-shed/ 15 min by foot) the urban block, (ii) green areas and trees, soil consumption and permeable/non-permeable surfaces, (iii) internal and external mobility (parking areas, bicycle paths and pedestrian routes, railways, public transport). In this case, within 500 m, there are many community-serving retailers, food shops and supermarkets, professional services, and hospitality services (B&Bs and Airbnb). Also, there is one preschool, one high school, one recreational-cultural centre, and many other community facilities. Block 279 is well-served by public transport, and some bicycle paths and pedestrian routes could be improved to enhance efficient, sustainable mobility. The artificialisation degree (AD), as the ratio between soil covering with artificial materials and the territorial area expressed as a percentage, accounts for 99%, and the built-up area is the main contributor (60%), together with asphalt surfaces and other non-permeable materials (21%). Only 9% is devoted to permeable/semi-permeable areas, and 10% is occupied by green areas (private and for shared use) with 44 trees.

The analysis at the building scale is based on the data included in the georeferenced maps (created in the first phases) and the consultation of the building permits of the Municipality of Bologna. These show that there are 11 main buildings for residential use and 9 secondary buildings hosting functions directly connected to housing. They were built between 1959 and 1963 and have an average height of 27.68 m, corresponding to 7 floors. They are also characterised by a *portico* with commercial activities on the ground floor and two basement floors for garages and warehouses. The predominant building type is multi-family row houses (MR) (82%), the roof type is flat (100%), the prevailing load-bearing structure is mixed, with both reinforced concrete pillars and

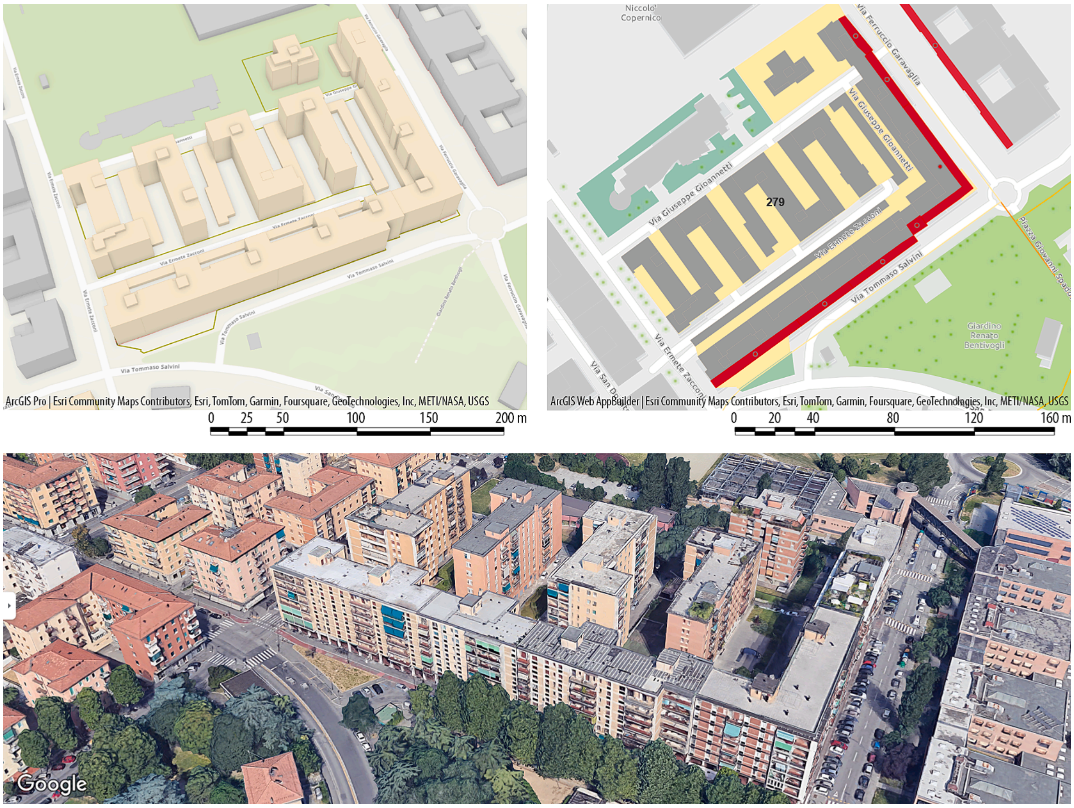


Fig. 1. Existing urban block in Bologna, in the neighbourhood "San Donato", used as an experimental application. On the left: 3D model. On the right: 2D map © 2024, Authors. The authors elaborated on data using 'ArcGIS Pro' software by Esri. Data source available online: Open Data, Bologna, https://opendata.comune.bologna.it/explore/?sort=modified, CC by 4.0.

beams, and masonry load-bearing walls (Masonry&Reinforced Concrete, MRC – 55%), only 27% of the existing buildings is realised with a reinforced concrete (RC) frame. The external envelope is made with solid *bolognese* bricks or perforated bricks without thermal insulation layers, and the internal floor slabs and roofs with hollow-core bricks (Appendix A – Stratigraphies of the conservation scenario as the existing state). The PD accounts for 0.09 inhabitants/m^2 with 1,385 potential inhabitants and 420 apartments distributed in 11 buildings, with three-room flats as the prevailing apartment type with an average size of 78 m^2. The number of potential inhabitants and apartments was calculated by considering 25–30 m^2 per person, following the Italian urban standard (included in the Italian Ministerial Decree 1444/1968) and the internal arrangement of single or double rooms represented in architectural drawings.

After the accurate study of the existing state, the intervention scenarios are defined: conservation (C), deep renovation (DR), and reconstruction (R). Also, the buildings' life cycle is evaluated by performing the LCA according to different timelines: 10 years (2030), 30 years (2050), and 60 years (2080).

The C evaluates the service life of the existing buildings, including the operational energy and water and the maintenance works without specific energy or seismic improvement. The existing buildings are modelled with the following assumptions: reinforced concrete load-bearing structure and hollow brick walls; no thermal insulation layers for walls or roof; single-glazed wooden windows; heating and domestic hot water (DHW) produced by natural gas boilers with traditional radiators. In Italy, natural gas plays a crucial role in space and water heating, accounting for 56.8% and 58.4% of the energy consumed for these end uses, respectively, compared to the European averages of 36.3% and 39.0% [39].

The DR includes some of the most common standard interventions used in recent years in Italy for energy retrofitting, such as the use of External Thermal Insulation Composite Systems (ETICS) with grey polystyrene for the insulation of the building envelope, the use of rigid polyurethane foam for the roof slab, the replacement of old windows with double-glazed windows with wooden frames, and the replacement of natural gas boilers and radiators for heating and DHW with an air-to-water heat pump and fan coil units. No seismic improvement is envisaged.

Finally, the R supposes demolishing the existing buildings and their reconstruction respecting the principles and guidelines defined within the R4R framework, such as: (i) use of circular and ecodesign strategies in the choice of materials and construction techniques, (ii) bioclimatic design, (iii) densification by providing a volumetric incentive of 20% for economic sustainability by constructing more dwellings than the existing state, (iv) desealing with an increase of permeable and green areas, (v) exclusion of fossil fuels and use of RES, (vi) enhancing sustainable mobility with pedestrian and bicycle routes, and the use of shared electric vehicles, (vii) inclusion of shared facilities for waste management, maintenance of green spaces, and other community services, (viii) single managing body for the whole process, (ix) maximum number of floors as two floors more than the average number of the existing state to avoid an excessive visual and dimensional impact on the existing urban fabric, (x) double windowed front for all the new dwellings.

The new urban block is designed in compliance with the mentioned guidelines and consists of NZEBs, respecting the current national prescriptions for seismic zones. The design phase is steered by defining a 'base unit' that can be aggregated and customised according to specific needs, and, at the same time, it allows for the construction process optimisation. In this case, the 'base unit' is made of eight residential floors with three apartments per stairway combining two different types of plan: module A and module B, whose spaces are defined by a 5 x 4.75 m structural grid, allowing for both proper lighting and ventilation of each dwelling. The 'base unit' comprises 24 flats, and the ground floor is designed to host community services and shops. Module A consists of one 2-room apartment (GFA: 62 m^2), one 3-room apartment (GFA: 78 m^2) and one 4-room apartment (GFA: 101 m^2). The module B consists of one 2-room apartment (GFA: 62 m^2) and two 3-room apartments (GFA: 84 m^2). Also, each module has its stairway (GFA: 24 m^2), and the total GFA per floor equals 266 m^2 per module. The different arrangements for 2-room, 3-room, or 4-room apartments correspond to the demographic trend, characterised by less numerous and older family units. More than half of the families are made up of 1 person (55.43%), only 22.98% are made up of 2 people and 11.18% of 3 people for the studied neighbourhood (San Donato) as of December 31, 2023 [40]. Looking at statistical data of the resident population divided into age classes as of December 31, 2023, almost ¼ is over 65 years old (23.23%), about ¼ is 0–29 years old (26.84%), and the remaining ½ is 30–64 years old (49.93%) [41].

The reconstruction project envisages the base units' aggregation according to the multi-family row house scheme, creating two main lines following the rectangular shape of the territorial area with a central park, pedestrian and bicycle routes, and recreation spaces (Fig. 2).

The new project changes the density parameters for the existing state, resulting in a 5% decrease in the FSI, a 38% decrease in the GSI, a 44% decrease in the vertical density ($VD = \Sigma$ (vertical surface)$_i$ / territorial area, where the vertical surface is the buildings envelope area, and i = ith building in the urban block [42]), and the creation of 60 more dwellings (480 apartments total) with new PD equal to 0.097 inhabitants/m^2 with 1,418 potential inhabitants.

A NZEB safe for seismic zones with a steel-wood hybrid structure was considered with steel pillars and beams and XLAM horizontal slabs, mainly constructed with dry construction techniques, choosing materials and systems fostering circularity, demountable solutions, adaptability and flexibility, and low environmental impact throughout the life cycle. Reinforced concrete is limited to the stairways as bracing elements and foundation beams. The external walls consist of OSB panels to create a closed cavity between pillars filled with mechanically blown glass wool. They are completed with ETICS made of self-supporting glass wool panels on the external side. On the internal side, a counter-wall for plants is insulated with glass wool panels and closed by heavy clay boards. The flooring and roofing slabs are made of XLAM with all the finishing layers, including green and paved roofs and ETICS made of self-supporting glass wool panels for the first floor. The stairway's reinforced concrete partitions are completed with the same insulation system. The use of an air–water heat pump combined with underfloor heating and fan coil units, as well as photovoltaic panels on the roof, is planned to ensure energy production from renewable sources. Specific and accurate information about the construction details for the three scenarios are collected in the supplementary materials attached to this contribution as Appendix A, and the performance results are summarised in Table 1. The choice of layers and materials for insulation in DR scenarios ensures compliance with minimum regulatory requirements for energy efficiency and corresponds to the most widespread solutions. The R is inspired by the circular model 'Integrho' [43,44], encouraging environmental sustainability and circularity. Additional variations on the 'Integrho' main building elements allow for polishing the final choice of materials for all the stratigraphies included in Appendix A. Specifically; they were analysed in terms of PE [MJ/m^2] and GWP [$kgCO_2e/m^2$]: five variations of the external wall with ETICS and ventilated facades, four variations of internal slabs, two variations of paved roof, three variations of green roof, and two variations of internal partitions between building units. The final choice focused on those solutions with lower impact both in terms of PE and GWP [45].

The construction details and plant systems for heating and cooling and DHW have been included in *Edilclima* software [46] to check that existing regulatory requirements for energy efficiency are met and calculate energy demand for heating, cooling and domestic hot water in each scenario. The Italian regulation evaluates the energy consumption of buildings as primary energy (PE_{tot}), which represents the energy supplied to the building by a system starting from the net energy demand of the envelope and taking into account the efficiency of the

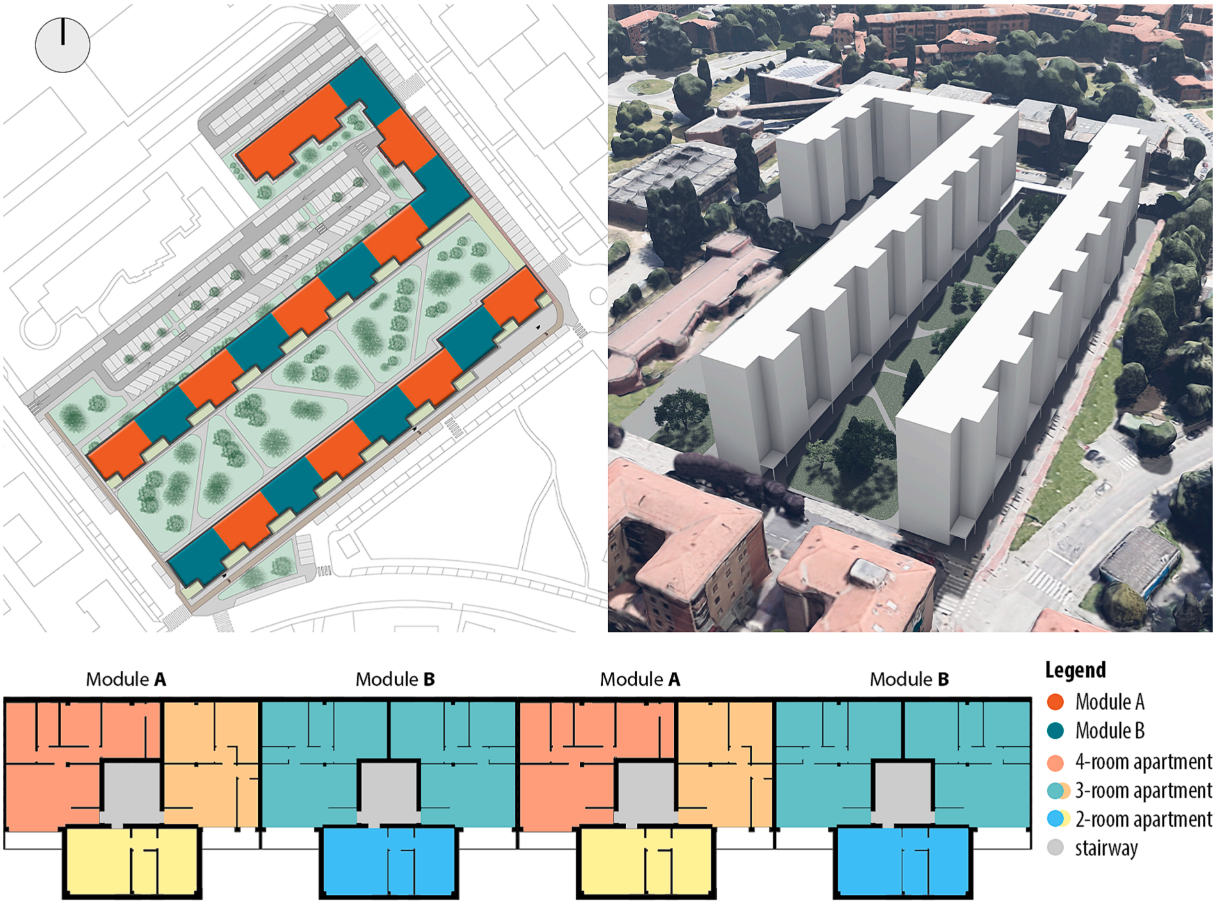


Fig. 2. Reconstruction: on the bottom, modules A and B; on the top: their aggregation as multi-family row buildings and 3D volumes view © 2024, Authors.

chosen system. PE_{tot} is expressed as the sum of renewable (PE_{ren}) and non-renewable primary energy (PE_{nren}) used for heating, cooling, and domestic hot water (DHW) in kWh/(m^2·y). For every base unit in each scenario: C (existing state), PE_{tot} is 164.37 kWh/(m^2·y), PE_{ren} is 0.22 kWh/(m^2·y), PE_{nren} is 164.15 kWh/(m^2·y); DR, PE_{tot} is 76.37 kWh/(m^2·y), PE_{ren} is 43.30 kWh/(m^2·y), PE_{nren} is 33.07 kWh/(m^2·y); R, PE_{tot} is 43.10 kWh/(m^2·y), PE_{ren} is 38.21 kWh/(m^2·y), PE_{nren} is 4.88 kWh/(m^2·y).

The base unit of the C and DR scenarios was chosen among the buildings located in block 279 as the most suitable with comparable characteristics to the base unit of the R: similar gross internal floor area (GIFA) per storey: 226 m^2 of the existing state vs 218 m^2 of the new building, the stairway serving three dwellings per floor, and the ground floor hosting commercial activities, 20 building units of the existing state vs 26 building units of the new building.

(2.3) Performing the LCA 'cradle to grave' of the three scenarios, considering three different service life, 10 years (2030), 30 years (2050), and 60 years (2080), to compare the figures in terms of GWP and PE and make further consideration in compliance with 2050 decarbonisation target. This phase follows the LCA methodology using the software *OneClickLCA* [47] to calculate the final impacts in terms of GWP ($kgCO_2e$) and PE (MJ), entering the information about the operational energy use (B6) and operational water use (B7) from energy simulation with the software *Edilclima* [46]. More specifically, the energy simulation assigned a thermal zone to each building unit, and the non-renewable primary energy for heating, cooling, and domestic hot water has been converted into equivalent quantities of natural gas and electricity to estimate the global warming potential associated with the operational energy use phase (B6) of each scenario [44]. The detailed system boundaries for each scenario are represented in Fig. 3. Two different states characterise each scenario: the present/current scenario is represented by the existing buildings, and the future scenario consists of the same buildings (with ordinary maintenance intervention) in C, the renovated buildings in DR, and the new buildings in R.

For each state, on the basis of some assumptions aligned with the goal and scope of this research, different LCA stages are considered or not in the assessment. More specifically, the A1–A5 phases for the existing buildings are not included in the calculation both for the C and DR as they were constructed in 1959–1963, and the impact of more than 40 years old materials and construction processes is not easily quantifiable as well as not relevant for research purposes. Also, the same impact (from the A1–A5 phases of the existing buildings) is not included in the R, as these buildings are assumed to be demolished. Otherwise, the A1–A5 phases for the materials and construction processes used for the deep renovation and reconstruction interventions were considered in the LCA.

Additionally, the impact of the C1–C4 phases was quantified for the existing buildings in the R scenario concerning the demolishing and disposal for implementing the reconstruction. The impact of the C1–C4 phases is also included in LCA for the renovated and new buildings in DR and R, as well as the existing buildings in the C. Finally, the impact of the B1–B5 and B6–B7 phases is calculated for all three scenarios in the future state, namely the existing buildings with conservation interventions (ordinary maintenance), the renovated buildings (in DR) and the new buildings (in R).

The LCA 'cradle to grave' was performed following the methodology provided by normative requirements [19,20]. The main scope of this study is to calculate the environmental impact in terms of GWP and PE, focusing on the different contributions of embodied carbon (EC) and embodied energy (EE), and operational carbon (OC) and operational

Table 1
Performance characteristics of the main stratigraphies of the building parts for the three intervention scenarios (C, DR and R). In bold: unchanged values in deep renovation from the conservation scenario/existing state © 2024, Authors.

CONSERVATION SCENARIO / EXISTING STATE	**WALL**			**FLOOR / ROOF**			
Parameter description	***EW*** ***_30 cm***	***SW*** ***_30 cm***	***PW***	***IF*** ***_16 cm***	***BF(−1) GF(0)*** ***_16 cm***	***PF*** ***_16 cm***	***RS*** ***_16cm***
U Thermal transmittance [W/(m^2·K)]	0.941	0.867	0.867	1.307	1.307	1.575	1.483
t thickness [mm]	330	330	330	250	250	250	290
M$_s$ surface mass (with plasters) [kg/m^2]	260	260	260	304	304	304	317
Ψ Periodic thermal transmittance [W/(m^2·K)]	0.412	0.314	0.314	0.457	0.457	0.772	0.651
thermal lag [h]	-8.4	-9.3	-9.3	-8.2	-8.2	-7	-7.6
DEEP RENOVATION SCENARIO	**WALL**			**FLOOR / ROOF**			
Parameter description	***EW*** ***_30 cm***	***SW*** ***_30 cm***	***PW***	***IF*** ***_16 cm***	***BF(−1) GF(0)*** ***_16 cm***	***PF*** ***_16 cm***	***RS*** ***_16 cm***
U Thermal transmittance [W/(m^2·K)]	0.178	**0.867**	**0.867**	**1.307**	**1.307**	0.193	0.19
t thickness [mm]	480	**330**	**330**	**250**	**250**	400	419
M$_s$ surface mass (with plasters) [kg/m^2]	275	**260**	**260**	**304**	**304**	319	389
Ψ Periodic thermal transmittance [W/(m^2·K)]	0.019	**0.314**	**0.314**	**0.457**	**0.457**	0.027	0.03
thermal lag [h]	-12.4	**-9.3**	**-9.3**	**-8.2**	**-8.2**	-10.4	-12.2
RECONSTRUCTION SCENARIO	**WALL**						
Parameter description	***EW-H*** ***_19.6 cm***	***EW-H-VF*** ***_19.6 cm***	***PW***	***EW-SH*** ***_26 cm***	***PW-SH***	***SW*** ***_19.6 cm***	
U Thermal transmittance [W/(m^2·K)]	0.110	0.109	0.185	0.117	0.112	0.431	
t thickness [mm]	386	451	310	323	345	300	
M$_s$ surface mass (with plasters) [kg/m^2]	123	137	166	75	86	532	
Ψ Periodic thermal transmittance [W/(m^2·K)]	0.005	0.005	0.051	0.022	0.021	0.034	
thermal lag [h]	-16.5	-17.0	-10.8	-11.2	-11.6	-11.7	
	FLOOR / ROOF						
Parameter description	***IF-H*** ***_16 cm***	***GF(0)***	***PF*** ***_16 cm***	***SH-F*** ***_16 cm***	***RF-P*** ***_16 cm***	***RF-G*** ***_16 cm***	
U Thermal transmittance [W/(m^2·K)]	0.198	0.463	0.124	0.158	0.099	0.099	
t thickness [mm]	336	342	446	644	568	757	
M$_s$ surface mass (with plasters) [kg/m^2]	127	426	150	136	133	264	
Ψ Periodic thermal transmittance [W/(m^2·K)]	0.013	0.052	0.002	0.004	0.005	0.005	
thermal lag [h]	-16.3	-11.5	-20.00	-17.7	-17.4	-17.4	

EW = external wall; SW = stairway wall; PW = partition wall between building units; IF = internal floor; BF(−1) = basement floor (level −1); BF(−2) = basement floor (level −2); GF(0) = ground floor (level 0); PF = portico floor (level 1); RS = roof slab; EW_H = external wall housing; EW_H-VF = external wall housing-ventilated facade; EW-SH = external wall shops; PW-SH = partition wall between shops; IF-H = internal floor housing; SH-F = shops' floor (level 1); RS-P = roof slab – paved; RS-G = roof slab – green roof;_00 = thickness of the layers interposed to/of the structural frame in cm.

energy (OE), in the three scenarios (C, DR, R). The EC and EE are connected to the carbon/energy embodied in materials and construction processes, and they refer to the A1–A5, B1–B5, and C1–C4 phases. The OC and OE are connected to the use and operational phases (B6 and B7).

The benefits and loads linked to the circularity benefit included in phase D have been excluded from this simulation, as more detailed and targeted analyses and other specific software would be required. The application scale is the urban block, whose results can be upscaled to the urban district and municipal area. The following assumptions are aligned with the goal and scope, and application scale: (i) exclusion of impacts related to internal and external paints, (ii) exclusion of impacts related to internal partitions and internal doors in each building unit, (iii) inclusion of the construction site impacts connected to the construction of the new buildings in the R scenario as average construction site impacts for temperate and southern climate zones in Europe [47], (iv) inclusion of the impact as global data of concrete frame buildings' demolition [47] for demolishing the existing buildings in the R scenario. Therefore, the construction site impacts and demolitions connected to DR intervention were not included in this LCA as their contribution was irrelevant in relation to the goal and scope, and implementation scale. The results are presented as EC, OC, and EE, OE in the whole-life carbon and whole-life energy assessment per [m^2·y]. The functional unit (FU) is assumed to be the m^2 of the GIFA (gross internal floor area) of the existing/renovated buildings and the reconstructed ones at three different time intervals (10 years, 30 years, and 60 years).

In C, the impacts from the use phase (B1–B7) and the end-of-life (C1–C4) have been calculated for the three periods with a GIFA equal to 2,034 m^2, which is the surface of the existing state's base unit consisting of nine floors above the ground. In DR, the impacts from the use phase (B1–B7) and the end-of-life (C1–C4) of the renovated building, from the A1–A5 of the materials used for the intervention have been calculated for the three periods with the same GIFA, equal to 2,034 m^2. Finally, in R, the whole life cycle assessment has been performed considering all the life cycle phases (A1–A5, B1–B7, C1–C4) of the new buildings plus the impact connected to the demolition of the existing ones for the three periods with a GIFA equal to 2,180 m^2, which is the surface of the design's base unit consisting of nine floors above the ground. The service life for each building part has been defined in compliance with the lifespans provided by RICS "Whole life carbon assessment for the built environment" (2nd edition) [22] to evaluate the impacts related to B5.

Finally, for the definition of the material passport of the existing buildings, the choice of generic materials, referred to Italy, is preferred. On the contrary, materials from a specific manufacturer from Italy (local) are preferred for the renovation intervention and construction of the new buildings. However, materials from bordering countries are also included if this option is unavailable. In this last case, the impact from transport (A4) was estimated using the distance from the factory to the construction site (Bologna). The bill of quantity for each building part and specific results for each LCA stage (A1–A5, B1–B5, B6, B7, C1–C4) are included in Appendix B, attached to this contribution. The summary results for each base unit in the three scenarios and time intervals are presented in the following section.

(2.4) The interpretation of the first results from LCA of the three scenarios is the last phase of the presented methodology and consists of critical reflection and discussions on the results.

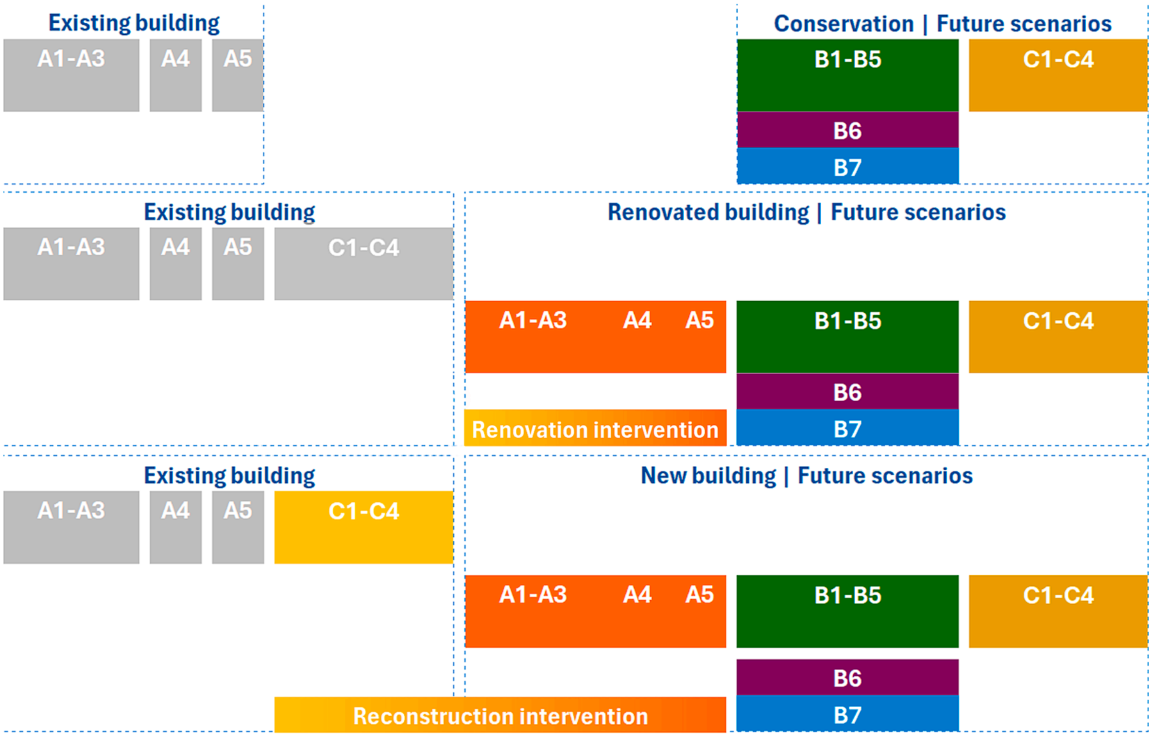


Fig. 3. System boundaries for LCA in each scenario (C, DR, R). LCA phases: A1 Raw material supply, A2 Transport, A3 Manufacturing; A4 Transport; A5 Construction–Installation process; B1 Use, B2 Maintenance, B3 Repair, B4 Replacement, B5 Refurbishment; B6 Operational energy use, B7 Operational water use; C1 Deconstruction demolition, C2 Transport, C3 Waste processing, C4 Disposal. In grey: excluded phases © 2024, Authors.

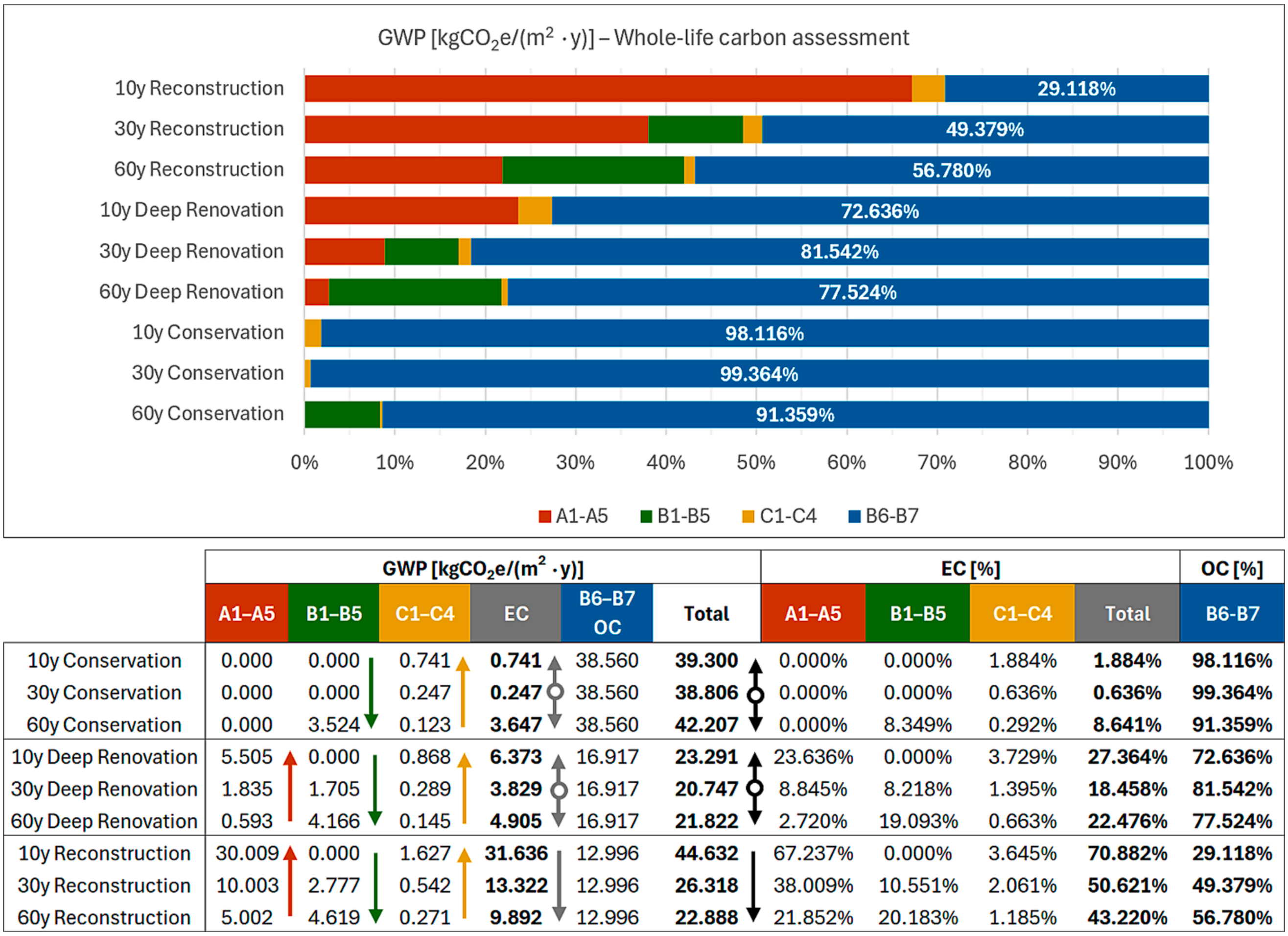
3. Results and Discussion

The LCA for the C shows that the impact in terms of GWP and PE is not sustainable from the short to the long term. The OC and OE resulted constant in the three periods with 38.56 $kgCO_2e/(m^2 \bullet y)$ and 599.37 $MJ/(m^2 \bullet y)$, and are responsible for the major impacts: OC (GWP, B6–B7) contribution accounts for 98% in 10 years and 91% in 60 years, and OE (PE, B6–B7) contribution accounts for 97% in 10 years and 92% in 60 years. These variations are connected to the share of EC and EE related to the end-of-life (C1–C4) and use (B1–B5) impacts. The end-of-life (C1–C4) impacts decrease as the calculation period increases. Their contribution is constant and divided by an increasing number of years. The EC of C1–C4 accounts for 1.88% in 10 years, 0.64% in 30 years, and 0.29% in 60 years. The EE registers a similar trend for C1–C4 (0.54% in 60 years, 1.14% in 30 years, and 3.39% in 60 years). The impact connected to the use phases B1–B5 is expected to increase as the period increases, from 0% in 10 and 30 years to 8% in 60 years for both EC and EE (Figs. 4, 5). The percentage values were calculated based on whole-life carbon and whole-life energy. In C, the percentage trend of OC and OE is decreasing, as the percentage trend of EC and EE is increasing.

The LCA for the DR shows that the contribution of OC and OE is relatively lower than C, accounting for 16.92 $kgCO_2e/(m^2 \bullet y)$ and 281.75 $MJ/(m^2 \bullet y)$. Also, OC (GWP, B6–B7) varies from 73% in 10 years to 78% in 60 years, and OE (PE, B6–B7) varies from 70% in 10 years to 78% in 60 years. These variations are connected to the share of EC and EE (A1–A5, B1–B5, C1–C4). More specifically, the EC of C1–C4 accounts for 3.73% in 10 years, 1.40% in 30 years, and 0.66% in 60 years; the EC of A1–A5 accounts for 23.64% in 10 years, 8.84% in 30 years, and 2.72% in 60 years. The EE registers a similar trend both for C1–C4 (1.00% in 60 years, 2.08% in 30 years, and 5.45% in 10 years) and A1–A5 (4.47% in 60 years, 9.27% in 30 years and 24.29% in 10 years). The impact connected to the use phases B1–B5 varies from 0% in 10 years to 8% in 30 years and 19% in 60 years for the whole-life carbon, and from 0% in 10 years to 8% in 30 years and 17% in 60 years for the whole-life energy (Figs. 4, 5).

In DR, the percentage trend of OC and OE is apparently increasing. The share of EC and EE is connected to the end-of-life (C1–C4) and ordinary maintenance intervention (B1–B5), plus the production, construction processes and transport (A1–A5). More specifically, the C1–C4 impact decreases as the calculation period increases, as does the A1–A5 impact. Meanwhile, the B1–B5 impact increases as the calculation period increases. However, as absolute values, B1–B5 impact is more relevant than [C1–C4 + A1–A5] in the long term. In fact, in the long period, the share of EC and EE related to B1–B5 are responsible for the highest EC/EE impact than the other phases, suggesting that the whole trend has reversed from the medium to the long period, considering that the OC/OE share is constant (Figs. 4–7). Finally, in DR, the percentage trend direction is equal to C: %OC and %OE is decreasing, as the %EC and %EE is increasing in the long period.

The LCA for R shows that the contribution of OC and OE is far lower than C and DR, accounting for 12.996 $kgCO_2e/(m^2 \bullet y)$ and 232.07 $MJ/(m^2 \bullet y)$. Also, OC (GWP, B6–B7) varies from 29% in 10 years to 57% in 60 years, and OE (PE, B6–B7) varies from 23% in 10 years to 47% in 60 years. These variations are connected to the share of EC and EE (A1–A5, B1–B5, C1–C4). The EC of C1–C4 accounts for 3.65% in 10 years, 2.06% in 30 years, and 1.18% in 60 years; the EC of A1–A5 accounts for 67.24% in 10 years, 38.01% in 30 years, and 21.85% in 60 years. In this case, the impact from the demolition of the existing building accounts for an increase of 58% and 34% in terms of GWP and PE of the C1–C4 phases, and the construction site impacts account for an increase of 6% and 5% in terms of GWP and PE of the A1–A5 phases. The EE registers a similar trend both for C1–C4 (1.00% in 60 years, 1.72%in 30 years, and 2.90% in 10 years) and A1–A5 (25.61% in 60 years, 44.12%in 30 years, and 74.31% in 10 years). The B1–B5 impact varies from 0% in 10 years to 11% in 30 years and 20% in 60 years for the whole-life carbon; and from 0% in 10 years to 14% in 30 years and 26% in 60 years for the whole-life energy (Figs. 4, 5). In the R scenario, the percentage trend of OC and OE is actually increasing. The share of EC and EE is connected to C1–C4,



	GWP [kgCO$_2$e/(m^2 ·y)]						EC [%]				OC [%]
	A1–A5	B1–B5	C1–C4	EC	B6–B7 OC	Total	A1–A5	B1–B5	C1–C4	Total	B6–B7
10y Conservation	0.000	0.000	0.741	**0.741**	38.560	**39.300**	0.000%	0.000%	1.884%	**1.884%**	**98.116%**
30y Conservation	0.000	0.000	0.247	**0.247**	38.560	**38.806**	0.000%	0.000%	0.636%	**0.636%**	**99.364%**
60y Conservation	0.000	3.524	0.123	**3.647**	38.560	**42.207**	0.000%	8.349%	0.292%	**8.641%**	**91.359%**
10y Deep Renovation	5.505	0.000	0.868	**6.373**	16.917	**23.291**	23.636%	0.000%	3.729%	**27.364%**	**72.636%**
30y Deep Renovation	1.835	1.705	0.289	**3.829**	16.917	**20.747**	8.845%	8.218%	1.395%	**18.458%**	**81.542%**
60y Deep Renovation	0.593	4.166	0.145	**4.905**	16.917	**21.822**	2.720%	19.093%	0.663%	**22.476%**	**77.524%**
10y Reconstruction	30.009	0.000	1.627	**31.636**	12.996	**44.632**	67.237%	0.000%	3.645%	**70.882%**	**29.118%**
30y Reconstruction	10.003	2.777	0.542	**13.322**	12.996	**26.318**	38.009%	10.551%	2.061%	**50.621%**	**49.379%**
60y Reconstruction	5.002	4.619	0.271	**9.892**	12.996	**22.888**	21.852%	20.183%	1.185%	**43.220%**	**56.780%**

Fig. 4. Results of LCA in terms of GWP, EC and OC for the three intervention scenarios (C, DR, R) for three periods (10, 30 and 60 years). The arrows represent the growing direction © 2024, Authors.

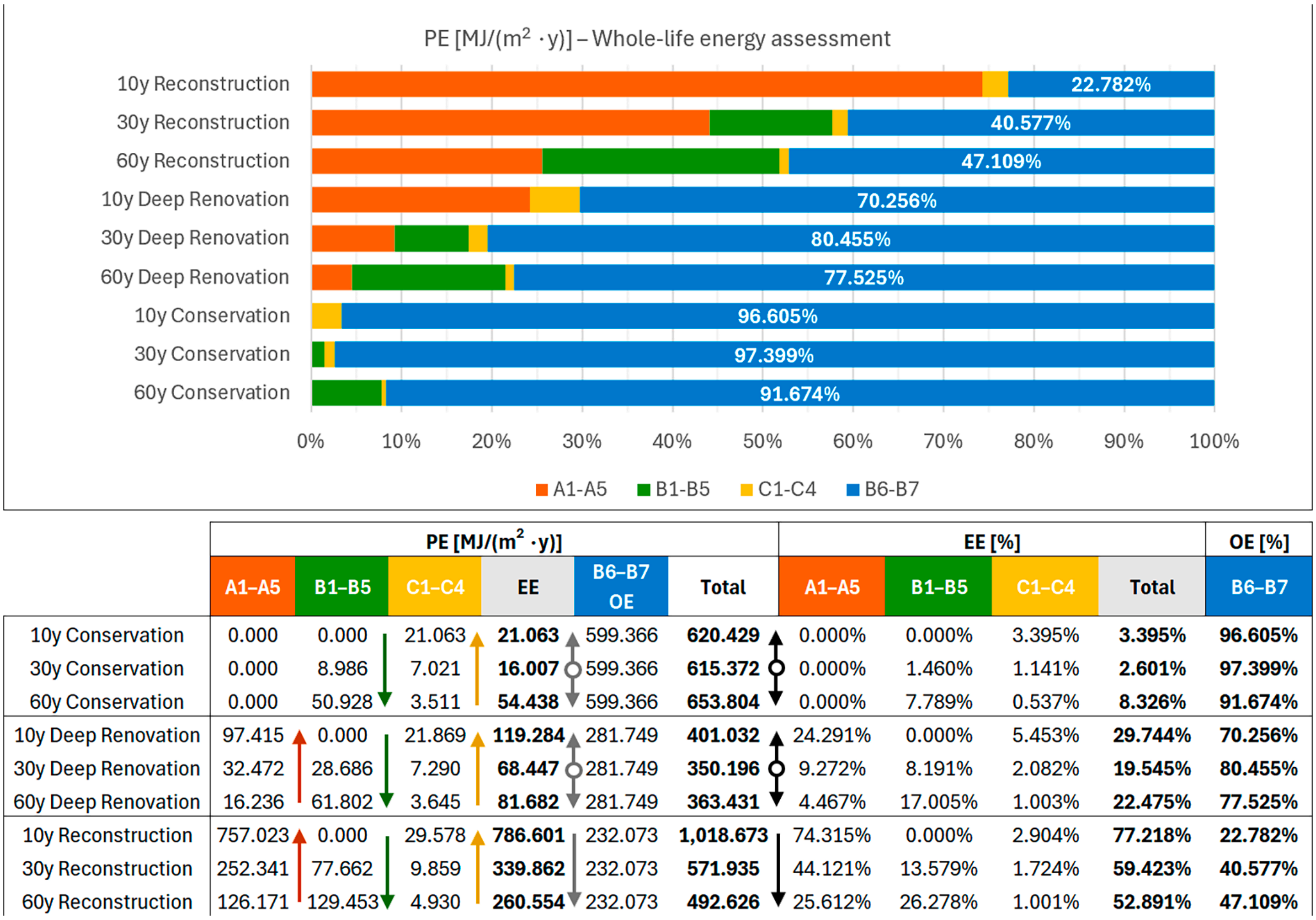
A1–A5, and B1–B5. As mentioned, the C1–C4 impact decreases as the calculation period increases, as does the A1–A5 impact. Meanwhile, the B1–B5 impact increases as the calculation period increases. However, as absolute values, B1–B5 impact is less relevant than [C1–C4 + A1–A5] in the medium and long periods. In fact, in the long period, the share of EC and EE related to [C1–C4 + A1–A5] are responsible for the highest EC/EE impact than the other phases (B1–B5), suggesting that the whole trend is constantly decreasing.

The whole-life carbon and energy assessments suggest that R is expected to have lower environmental impacts for extended periods. On the contrary, both C and DR are not sustainable, showing an increasing impact over long periods (Figs. 6, 7).

To further explore and validate the LCA results, a simulation with a different FU was performed. The FU as [m^2] of GIFA may have biased the results as, in the R scenario, we assume to construct 26 building units (24 dwellings and 2 shops) with an average gross floor area (GFA) of 80 m^2, while in C and DR ones, we have 20 building units with average GFA of 78 m^2. Assuming to redefine the FU as the building unit [BU], the results of LCA in terms of GWP and PE are divided for the number of building units constructed in the reconstruction scenario (26) and the number of existing/renovated building units in the conservation/deep renovation scenario (20). The EC, EE, OC, and OE are expressed per building unit (BU) per year [BU•y]. In this case, the increasing number of building units in the R scenario is taken into account. Even if the most recurring and easily comparable FU is the [m^2], some research demonstrates that with different building types, the buildings with the most extensive constructed area result in less impact [48]. However, this is not universally correct, especially considering the number of inhabitants or building units for each type.

The LCA results updated with the new FU [BU•y] demonstrate that R is more convenient than C in terms of GWP even in the short period, and in terms of PE starting from the medium period; the DR is more convenient than C both in terms of GWP and PE in the short, medium and long periods. Finally, R also results more convenient than the DR in the long period in terms of GWP (1,919.33 vs 2,219.28 kgCO$_2$e/(BU•y) in 60 years), and even in the medium period, the gap is relatively short (2,207.22 vs 2,109.93 kgCO$_2$e/(BU•y) in 30 years). However, the DR still resulted in more convenience than R in terms of PE for all the calculation periods, showing the relevance of choosing less energy-intensive materials to reduce the EE of A1–A5, B1–B5 and C1–C4 phases, which is equal to seven times the same one of DR, after 60 years (Figs. 8, 9). Finally, with this FU update, the long-term trend for both C and DR is growing, preventing them from reaching the net zero target proposed by the EU. Detailed results from LCA with both FUs are included in Appendix B.

One of the main limitations of this study is that LCA-based simulations have been performed in a non-dynamic dimension: impacts were calculated for different periods (10, 30 and 60 years) and then distributed over the years, supposed to be yearly constant. Then, they do not correspond to 'real-time' GHG emissions. Also, the presented results do not consider the rise in global temperature and its relative influence on energy consumption for heating and cooling as well as CO$_2$ concentration due to climate change in the future, and how this would affect the economic sectors and the global emissions from buildings. However, this approximation is aligned with the goal and scope of this research and the application scale. Further and more accurate dynamic analyses could be



	PE [MJ/(m² ·y)]						EE [%]				OE [%]
	A1–A5	B1–B5	C1–C4	EE	B6–B7 OE	Total	A1–A5	B1–B5	C1–C4	Total	B6–B7
10y Conservation	0.000	0.000	21.063	**21.063**	599.366	**620.429**	0.000%	0.000%	3.395%	**3.395%**	**96.605%**
30y Conservation	0.000	8.986	7.021	**16.007**	599.366	**615.372**	0.000%	1.460%	1.141%	**2.601%**	**97.399%**
60y Conservation	0.000	50.928	3.511	**54.438**	599.366	**653.804**	0.000%	7.789%	0.537%	**8.326%**	**91.674%**
10y Deep Renovation	97.415	0.000	21.869	**119.284**	281.749	**401.032**	24.291%	0.000%	5.453%	**29.744%**	**70.256%**
30y Deep Renovation	32.472	28.686	7.290	**68.447**	281.749	**350.196**	9.272%	8.191%	2.082%	**19.545%**	**80.455%**
60y Deep Renovation	16.236	61.802	3.645	**81.682**	281.749	**363.431**	4.467%	17.005%	1.003%	**22.475%**	**77.525%**
10y Reconstruction	757.023	0.000	29.578	**786.601**	232.073	**1,018.673**	74.315%	0.000%	2.904%	**77.218%**	**22.782%**
30y Reconstruction	252.341	77.662	9.859	**339.862**	232.073	**571.935**	44.121%	13.579%	1.724%	**59.423%**	**40.577%**
60y Reconstruction	126.171	129.453	4.930	**260.554**	232.073	**492.626**	25.612%	26.278%	1.001%	**52.891%**	**47.109%**

Fig. 5. Results of LCA in terms of PE, EE and OE for the three intervention scenarios (C, DR, R) for three periods (10, 30 and 60 years). The arrows represent the growing direction © 2024, Authors.

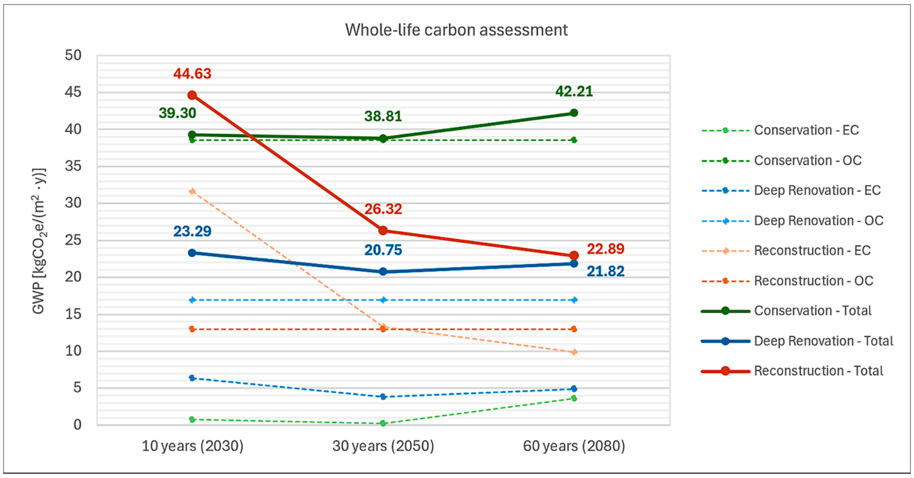


Fig. 6. Whole-life carbon assessment for the three intervention scenarios (C, DR, R) for three periods (10, 30 and 60 years) © 2024, Authors.

performed in a real pilot case.

4. Conclusions

The construction sector is undoubtedly highly impactful. Feasible and concrete measures for regenerating the built environment and reducing its environmental impact are urgent to meet the decarbonisation target proposed by the EU by 2050. In this context, circular construction solutions with a high percentage of reused and reusable materials and NZEBs whose needs are fully met by renewable energy sources (RES) without using fossil fuels are the leading elements to promote the transition to climate neutrality. This contribution compares and investigates three different intervention scenarios (conservation, deep renovation, and reconstruction) in three time intervals (10, 30, and 60 years) following the LCA methodology applied to an existing urban block located in the first urban periphery in Bologna (Italy).

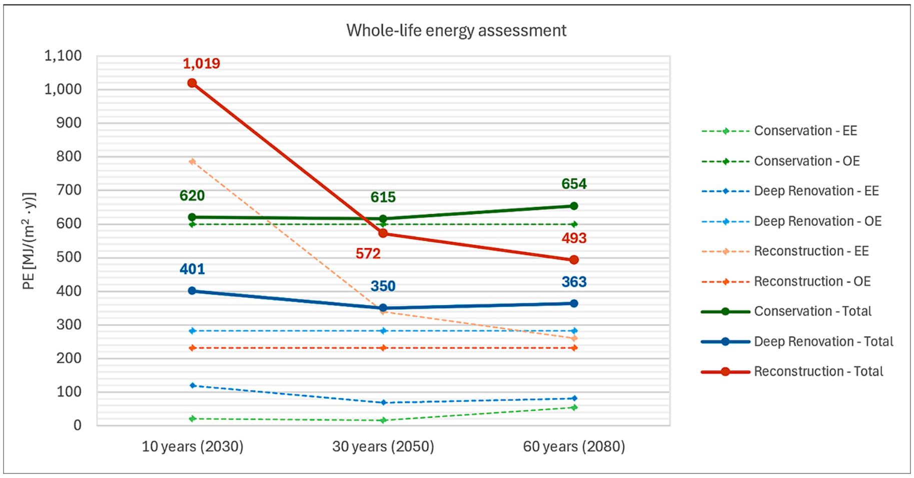


Fig. 7. Whole-life energy assessment for the three intervention scenarios (C, DR, R) for three periods (10, 30 and 60 years) © 2024, Authors.

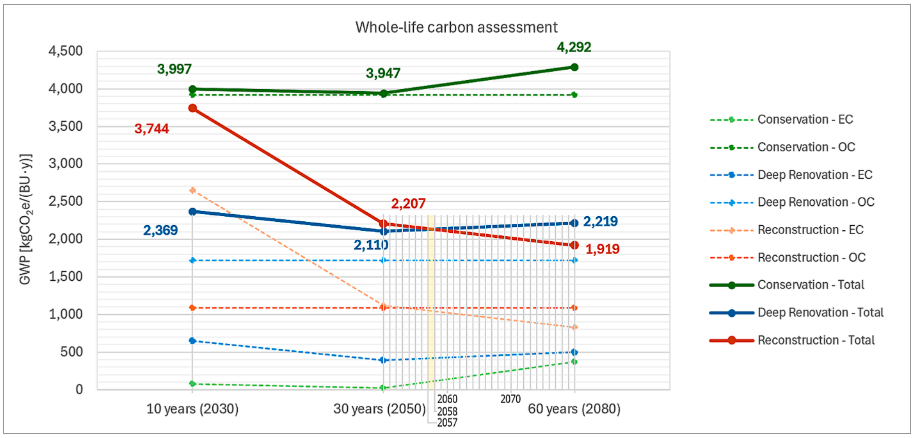


Fig. 8. Whole-life carbon assessment for the three intervention scenarios (C, DR, R) for three periods (10, 30 and 60 years) with the new FU © 2024, Authors.

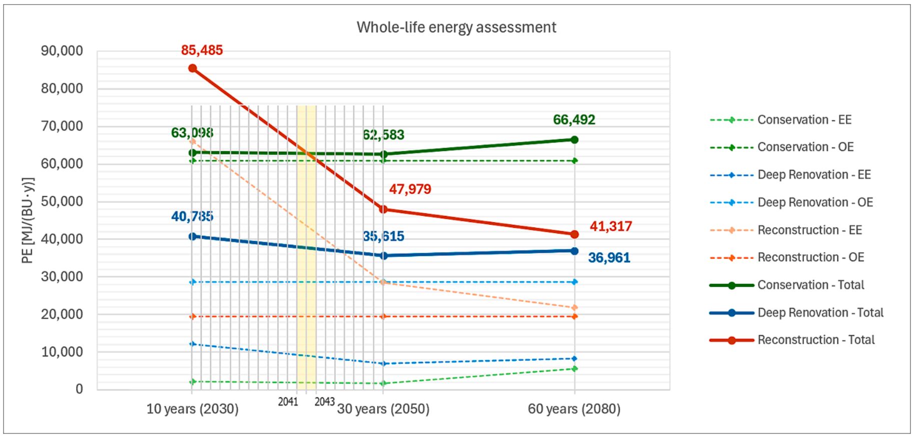


Fig. 9. Whole-life energy assessment for the three intervention scenarios (C, DR, R) for three periods (10, 30 and 60 years) with the new FU. © 2024, Authors.

The presented simulation demonstrates that the contribution from end-of-life (C1–C4) and production, construction processes and transport (A1–A5) finally increases in C and DR scenarios, and even if, after 60 years period, the EC and EE still represent the minor part of the whole, their impact is expected to grow as the period increases. In DR, the primary benefit is due to the high reduction in operational phases (B6 and B7) if compared to C (Figs. 5, 6). However, this is not sufficient to reach the net zero target: in the short and medium periods, the EC/EE trend is decreasing; in the long term, they are growing, and the benefit from the reduction in operational phases will be progressively more irrelevant leading to a further increasing in more extended periods (more than 60 years old). On the contrary, in R, the contribution from end-of-life (C1–C4) and production, construction processes and transport (A1–A5) progressively decreases, and even if, after 60 years period, the EE and EC still represent the major part of the whole (43% for EC, and 52% for EE), their impact is expected to decrease as the period increases, and the global trend resulted decreasing. In R, the benefit is directly related, firstly, to the reduction in operational phases (B6 and B7), whose contribution is lower than DR (GWP = 12.996 $kgCO_2e/(m^2•y)$ and PE = 232.073 $MJ/(m^2•y)$). Conversely, the choice of circular materials and construction solutions allows for minimising their impact of end-of-life, product and construction processes and use stages (C1–C4, A1–A5, B1–B5). These results are aligned with the future trend of new buildings, whose most relevant impact will be connected to the EC/EE and the use of circular solutions, if we assume that operational phases will be nearly zero thanks to RES. The significant reduction in the impacts of the operational phases in R and DR is strongly influenced by the ability to leverage RES through heat pump systems for heating, cooling, and DHW production. Indeed, the annual energy consumption from the electricity grid in the R scenario (designed to meet minimum regulatory standards with 31.2 kW peak photovoltaic capacity installed on 26.0 kW required) is 4,469 kWh/year but would increase to 28,819 kWh/year in the absence of renewable energy sources. This underscores the critical contribution of RES in reducing the impacts of the operational phase of buildings.

LCA simulations prove R is more convenient than C and DR in long periods if we use circular materials and construction solutions to minimise the EC and EE impacts and reduce the operational phases' impacts (OC and OE) using RES. Standard DR is still more convenient than R in the medium term, but not in the long, as the EC and EE impacts will grow, preventing it from reaching the net zero target.

The reconstruction scenario within the R4R strategy is a valuable alternative when applied to existing buildings constructed without a regulatory framework for energy efficiency and seismic safety. Minor interventions leading to a partial renovation are extremely common. Even if they meet high energy savings, they do not include seismic safety improvements, and no attention is paid to the choice of materials. They will extend buildings' service life, but they are not aligned with the decarbonization target in the long term.

The urban regeneration according to the R4R strategy needs further investigation to: (1) compare other reconstruction designs with different materials and construction solutions to reduce the impact in terms of PE; (2) include the contribution of biogenic carbon and LCA phase D to estimate the benefits from circular construction solutions, also with the support of other specific software; (3) implement and extend this simulation to other urban blocks, to have the same data for each archetype and compare the results for a larger sample following the same guidelines; (5) include a cost estimate to assess the economic feasibility of interventions; (6) extend the research by considering practical-operational aspects related to inhabitants' disturbance; (7) integrate these results into georeferenced maps to create interactive maps with environmental impact data referred to urban blocks' territorial area.

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CRediT authorship contribution statement

Anna Chiara Benedetti: Writing – original draft, Software, Methodology, Data curation, Conceptualization. **Carlo Costantino:** Writing – review & editing, Software, Methodology, Data curation, Conceptualization. **Rocco Lobosco:** Software. **Giorgia Predari:** Validation, Supervision, Methodology. **Riccardo Gulli:** Validation, Supervision, Methodology.

Declaration of competing interest

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

Appendix A & B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2024.115270.

Data availability

Data will be made available on request.

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