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Iso-performance retrofit solutions adopting a Life Cycle Thinking approach

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Abstract

Since the requalification of the existing building stock has become a priority, many national incentives have been allocated in the last years. To avoid a waste of such relevant economic effort, a deep and systematic integrated approach to the retrofit of the built environment should be considered, also pursuing sustainability, safety, and resilience at the same time. This may be pursuit only if a Life Cycle Thinking (LCT) approach is addressed, aimed at reducing costs and impacts in each phase of a building life cycle. A LCT approach not only may affect the material to be used for the retrofit, but it undermines the usual modus operandi right from the preliminary design phase of the intervention; for example, the structural details of the strengthening solution must be conceived to be easily off-site prefabricated, transported and assembled, and demounted and re-assembled in a different way at the end-of-life. In this paper, different iso-performance strengthening solutions are compared through the application to a reference case study considering the whole life cycle of the retrofitted building. All the considered structural solutions were then coupled to the same energy recovery intervention, allowing the building to shift from an energy class E to a class A1.

Keywords: *Integrated retrofit approach; Life Cycle Thinking; Life Cycle Assessment; Seismic retroit.*

1. Introduction

It is recognized that the existing building stock is obsolete, energy-demanding, and seismically vulnerable, and, therefore, it requires a deep and integrated renovation Gkatzogias et al. (2020). Such a renovation is now acknowledged as a priority, considering the recent global decarbonization targets and considering that, in Europe, the current building stock represents about the 80% of the stock of the 2050 BPIE (2011). In the last years, many national incentives have

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been allocated to renovate the existing buildings; however, they were usually adopted to carry out uncoordinated and uncoupled retrofit interventions. This was often a missed chance to renovate the existing stock with an integrated approach, overcoming all the building deficiencies at the same time and pursuing sustainability, safety, and resilience (Marini et al. ,2014). To meet such a need, the scientific debate focuses on holistic renovation from outside (Marini et al., 2014); however, this may not be enough. To conceive truly sustainable interventions, a Life Cycle Thinking approach, aimed at reducing all the possible economic, social and environmental impacts along the building life cycle, should be embraced Passoni et al. (2022a), Passoni et al. (2022b).

The effectiveness of such an approach to the renovation with respect to traditional retrofit actions emerges both during the construction time, when addressing the barriers to the renovation such as the inhabitant relocation and the existing building downtime, and when broadening the time frame of the analyses, shifting from the construction time to the whole building life cycle. A Life Cycle Thinking (LCT) approach for the design of retrofit interventions not only entails the use of recyclable/reusable and biobased materials, but also encourages the adoption of prefabricated components and standardized connections, allowing for easy construction and dismantling, and the adoption of reparable, easily maintainable, adaptable and fully demountable solutions, also guaranteeing, at the end-of-life, the selective dismantling and reuse or recycle of the components to reduce construction waste. A complete overview of LCT-based design objectives and principles is presented in Passoni et al. (2022a).

As far as integrated (i.e., seismic, energy, and architectural) retrofit interventions from the outside is concerned, many techniques have recently been proposed. As for the seismic retrofit layer of the interventions, additional exoskeletons realized with different techniques and materials have been studied by Marini et al. (2014),and Zanni et al., (2021). In particular, exoskeletons may be conceived as shear wall structures or shell structures. In the former case, additional shear walls are added to the building, lumping the lateral force resisting system into few elements; while, in the latter case, the whole length of the façade may be exploited to create a thin lateral force resisting box system. The solutions may be realized adopting different structural materials, i.e., steel, timber, or reinforced concrete (RC). Both these systems may be designed to have the same structural performances, thus defining iso-performance solutions.

In this paper, different iso-performance strengthening solutions are compared through the application to a reference building. Wall and shell solutions, made of different materials, and conceived to be either traditional or in accordance with an LCT approach are considered. All the structural solutions are then coupled to the same energy recovery intervention, allowing the building to shift from an energy class E to a class A1.

In Section 2 the reference building is presented. The structural, energy and architectural retrofits are described in Section 3. For each intervention, construction costs and impacts in terms of Global Warming Potential, Use of Fresh Water, and Non-Hazardous Waste Disposal are evaluated in Section 4. Some considerations are drawn in Section 5.

2. Reference building

The reference structure is a residential RC building located in the Brescia province (Italy) and built in the '70s. The structure has an L-shaped plan consisting of two staggered structural units (herein to referred as 'A' and 'B') connected by a central staircase core. The two units are set at different heights, thus leading to a significant vertical geometric irregularity. The Building A has a rectangular plan (12.28x8.12) m, inter-story height equal to 3.06 m at the ground floor, and 3.15m at the upper floors; Building B has a rectangular plan (13.60x9.80) m, develops at +1.05 m over a RC basement, and is characterized by an inter-story height equal to 3.10 m at the ground and first floors and 2.95 m at the top floor. The total covered area is equal to about 230 m^2 at each floor (**Fig. 1**). All the information about the reference case can be found in ReLuis (2019-21).

The bearing structure is made of 2-dimensional RC frames and was designed for gravity loads only. Floors are made of a one-way RC beam and clay block floor system featuring a 3 cm RC overlay for a total thickness of 19 cm. The staircase core is a RC shell; however, since the structural details were not conceived to ensure a global behavior among the three walls, they are regarded as two independent walls. The thickness of the stairwell walls varies between 20 cm and 25 cm. The staircase walls lay on independent beam foundations. As for the non-structural elements, infill walls are made of two layers of hollow bricks with two outer layers of plaster. According to the regulation code of the time of construction, concrete C20/25 and steel Feb32k (f_{ym}=315 MPa, f_{tk}=490 MPa) are considered.

The reference building is modeled with the software MidasGen (2019). Both structural and nonstructural elements are modeled as beam elements and their inelastic behavior is accounted by means of lumped plastic hinges. More precisely, the strength and deformation capacity of beams and columns are modeled according to the formulation suggested in the European building code (EC8, CEN 2005). Infill walls are modeled with two compression-only diagonal struts converging in the beam-column joints as proposed by Decanini, Gavarini e Bertoldi (1993). The non-linear behavior of the infill walls is described by means of the FEMA infill strut axial plastic hinge (2003); the cracking force and the peak force were evaluated according to Decanini et al. (1993), while the cracking drift and the peak drift were set in accordance with the common values of 0.3% drift for minor cracking, and 0.5% drift for the infill wall failure as proposed by Sassun, et al. (2016).

As for the boundary conditions, columns are considered as fixed at the base, while for the staircase walls a rotational spring (k_θ=320000 kNm) is introduced to model the existing foundation system considering a soil stiffness equal to 0.1 N/mm^3. More details can be found in Reluis (2019-21). To take into account the RC walls of the basement of Building B, elastic columns were placed with an increased flexural stiffness (amplification factor equal to 100 are modeled).

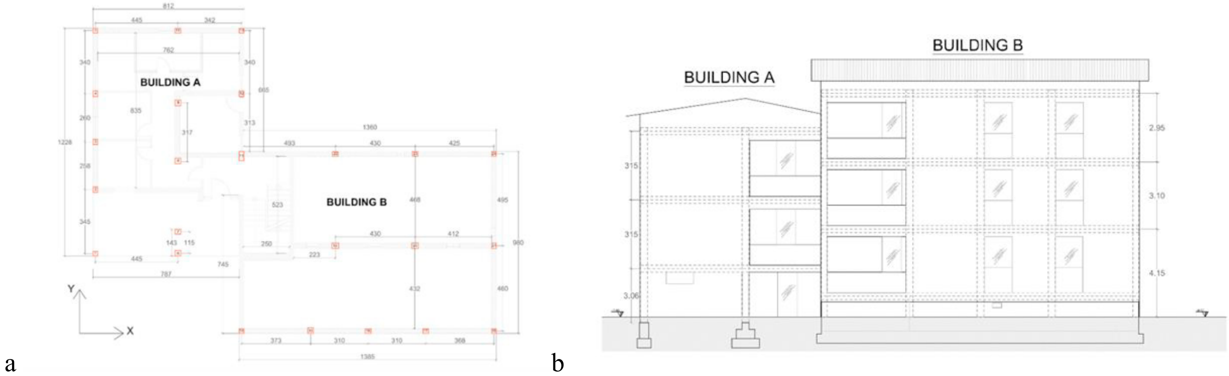

Fig. 1. (a) Existing building plan; (b) Existing building elevation (© ALER Brescia-Cremona-Mantova).

2.1. AS-IS condition assessment

The structural response of the existing building was obtained from nonlinear static analyses and the seismic vulnerability assessment was carried out following the N2 method by Fajfar (2000) and NTC (2018). The reference building did not satisfy the displacement demands associated with both Life Safety Limit State (LSLS) and Collapse prevention Limit State (CLS); a minimum seismic vulnerability index equal to ζ_E=0.59 was obtained, which corresponds to a Seismic class C.

The energy performance assessment was carried out considering the plants and the closures. In the analysis, the following hypotheses were considered: heating set point: 18-21°C; cooling set point: 26°C; relative Humidity +50%; appliances load: 5-15 W/m2; "inexpensive" average user; assumed thermal inputs; unlimited power plants (to evaluate loads). The analysis was performed using the Trnsys dynamic simulation program. The performances obtained for the reference building correspond to an Energy class E according to the Italian energy classification (post-2019).

3. Iso-performance seismic retrofit solutions

Four iso-performance seismic structural retrofit solutions were designed considering different technologies. All the solutions were then coupled to the same energy intervention.

3.1. Structural retrofit

From a structural point of view, the retrofit solutions are based on the following principles:

- The seismic retrofits are carried out from the outside of the building to solve two of the major barriers to the renovation of the existing buildings, namely: the need to relocate the inhabitants and the extended downtime required during the construction works Krimgold, Hattis, & Green (2004); BPIE (2011); La Greca & Margani (2018);
- The serviceability of the retrofitted building is guaranteed also for lower-probability earthquakes to reduce, or even avoid, downtime and post-earthquake repair costs. More restrictive design targets are thus considered with respect to the current practice, according to the principles of Life Cycle Structural Engineering by Passoni et al. (2022a);
- To make a reasonable comparison among the different retrofit solutions, all the proposed interventions lead to the same structural performances of the retrofitted building, i.e. the buildings have similar capacity curves and satisfy the Life Safety Limit State (LSLS).

The preliminary structural design of the retrofit solutions is based on the design spectra proposed in Labò et al. (2019). These spectra plot the required ductility (ratio between the maximum design displacement experienced by the retrofitted building when subjected to the design earthquake and the yield displacement of the existing building) as a function of the stiffness ratio between the retrofit system and the existing building, and they thus allow to define a preliminary estimation of the stiffness of the retrofitted system (existing building + exoskeleton) and, therefore, of the sole exoskeleton. The solutions are either shell and wall systems and are all designed according to a LCT approach with the exception of solution 3. All the solutions are here briefly described; further details can be found in ReLuis, (2019-21).

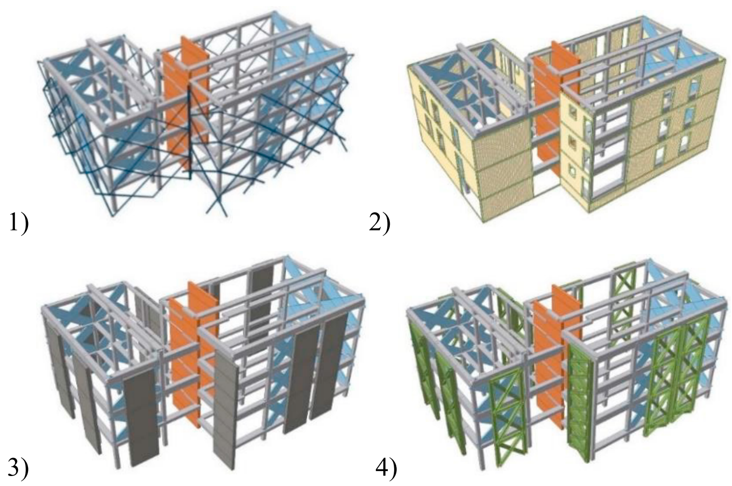

Fig. 2. FEM of 1) Solution 1, 2) Solution 2, 3) Solution 3, 4) Solution 4.

- Solution 1 – A diagrid exoskeleton is applied to the structure (Fig. 2.1). Diagrids are shell structures, in which the shell behavior is triggered by a lattice structure. Horizontal and diagonal elements are arranged in order to gain structural integrity through triangular modules composed of 2 diagonals and 1 horizontal element by Yadav & Garg, (2015), and Labò et al. (2021). The diagonal diameters range between 219.10 mm and 76.1 mm with thicknesses ranging between 20.0 mm and 3.2 mm, respectively.
- Solution 2 – A new wooden shell extending over the entire facades, made of Cross Laminated Timber (CLT) panels and strengthened with steel frames in correspondence of the window opening, is adopted. The technique was initially developed in the Industrial Research Project “AdESA: a new solution for the Energy-Structural-Architectural retrofit of existing building”. The design of all the retrofit components is based on the application of the design method described in Zanni et al. (2020). CLT panels with thicknesses ranging between 120 mm and 180 mm were implemented and connected each other by ϕ4/50mm nails. As for the steel frames, HEA120 were placed at the corners of the shell, and HEA140 were placed around the window openings.

- Solution 3 – A more traditional solution is adopted, which implements twelve new shear walls installed in close proximity to the building façades. The walls are made of cast-in-place RC elements with cross-section (0.25x2.50) m^2.
- Solution 4 – The solution resembles Solution 3, except that, in this case, twelve steel braced shear walls are adopted. HEB180 were used for columns while HEB120 for beams and diagonals.

In all the solutions, a steel stringcourse is introduced and connected to the perimeter chords (steel plates (250x15) mm were introduced and connected to the existing structure with ϕ20/250÷450 mm studs), having the functions to connect the exoskeleton to the existing structure and, together with transversal steel ties, to improve the capacity of the existing beam-and-block floor diaphragms.

For each solution, a new foundation system was designed. As for the shell solutions (Solutions 1 and 2) RC beams (70x100) cm^2 around the whole perimeter were connected by ϕ20/20 cm studs, and 16 micro-piles ϕ150mm L>15m (Capacity ±243kN) were designed. As for the shear wall solutions (Solution 3 and 4), 70x100x400 cm RC beams were designed and connected by ϕ20/20cm studs under each shear wall, and a total of 90 micro-piles ϕ150mm L>15m (Capacity ±243kN) were designed to withstand the bending moments of the new RC foundations.

The capacity curves of the iso-performance solutions are plotted in Fig.3a; the ultimate capacity of each curve (defined in correspondence of a load loss equal or higher than 15%) is indicated with the "X" symbol. In Fig.3b their bilinear curves are plotted in the ADRS Spectrum. Assuming the lower of the indices obtained, the seismic risk class of the retrofitted building is A+ according to the IS-V classification.

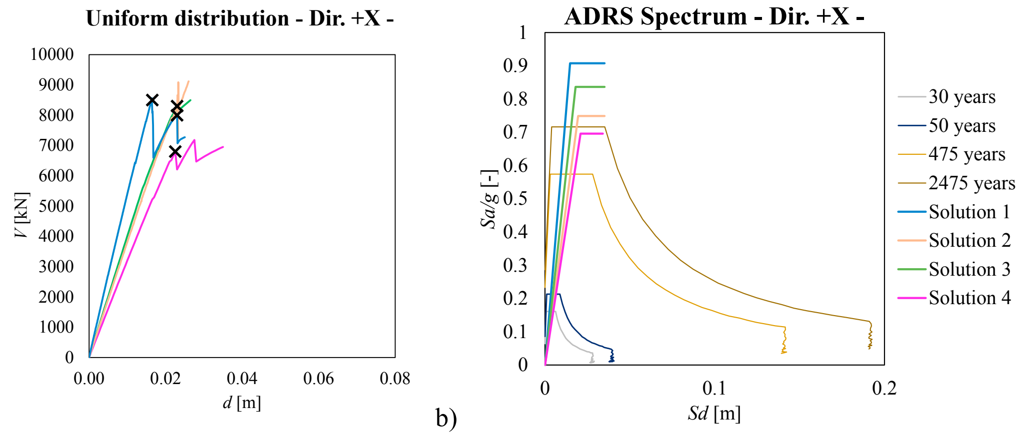

Fig. 3. a) Capacity curves of the iso-performance solutions in the X-Direction, b) Bilinear curve of the equivalent systems for the considered retrofit solutions in ADRS.

3.2. Energy retrofit

The energy retrofit is achieved by a primary intervention on the envelope, aimed at reducing the energy demand, and a secondary intervention, aimed at reducing the energy consumption by optimizing the energy production system. The former consists in the optimization of the vertical and horizontal opaque components by adding a thermal insulation coating and in substituting the transparent building components with outer doors and windows with high energy efficient frames and triple glazing. As for the vertical closures, an additional layer of polystyrene EPS insulation panels of 18 cm thickness is added along the walls, except for the area of the balconies, where polyurethane panels with 10cm thickness are adopted for saving living space. Along the horizontal closures, a 16 cm layer of rock wool is added to the last floor, and two different kinds of thermal insulating layers are added on the cellar floor (polyurethane panels of 7 cm thickness for the floors at the ground level and polystyrene EPS insulation panels of 10 cm thickness for the floors above the crawl space). Finally, polyurethane panels with 10 cm thickness are added at the porch ceiling. The secondary intervention consists in the substitution of the boiler for the production of domestic hot water with high-efficiency boilers.

The energy audit procedure requires an assessment of both the external dispersing structures and the plant subsystems. As for the dispersing structures, an insulated wall with a transmittance U = 0.303 W/m^{2}K along the sides and a floor with a transmittance U = 0.203 W/ m^{2}K in coverage have been considered.

The analysis was performed using the Trnsys dynamic simulation program (Figure 4a). In particular, for heating there was a peak thermal load of 21 kW and an annual thermal load of 38169 kWh (68 kWh/m^{2}a); for cooling, a peak thermal load of 9 kW and an annual thermal load of 3930 kWh (7 kWh/m^{2}a) resulted. These performances correspond to an Energy class A1 of the building in post-intervention conditions (classification post-2019). The comparison between the performances in terms of monthly thermal load before and after the intervention is shown in Figure 4b by ReLuis (2019-21).

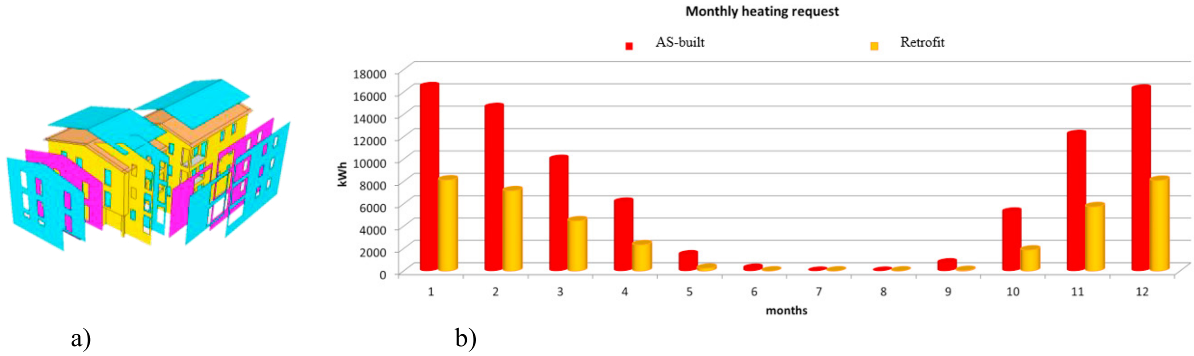

Fig. 4. a) Trnsys Model of the building, b) Comparison of the monthly heating request between the As-Is condition and the post-intervention.

4. Construction costs and Life Cycle Assessment (LCA) of the structural alternatives

4.1. Construction costs

The construction costs of each solution are evaluated and analyzed by decomposing the costs into macro-category of the intervention. In general, solutions have similar total costs, but the cheapest is the timber solution (Sol. 1), and the most expensive is the steel wall solution (Sol. 4). Analyzing the structural costs breakdown, it is useful to point out that for the wall solutions, a major share of the total cost is associated with the foundation system, while in shell solutions, the largest share of the cost is associated with the superstructure. In the shell exoskeletons (Sol. 1 and 2), extending the intervention to the entire façade results in a lower stress on the foundation system; on the contrary, in the wall exoskeletons (Sol. 3 and 4), more micropiles are required to resist the high load transferred to the foundation by the shear walls, hence the foundation cost is higher.

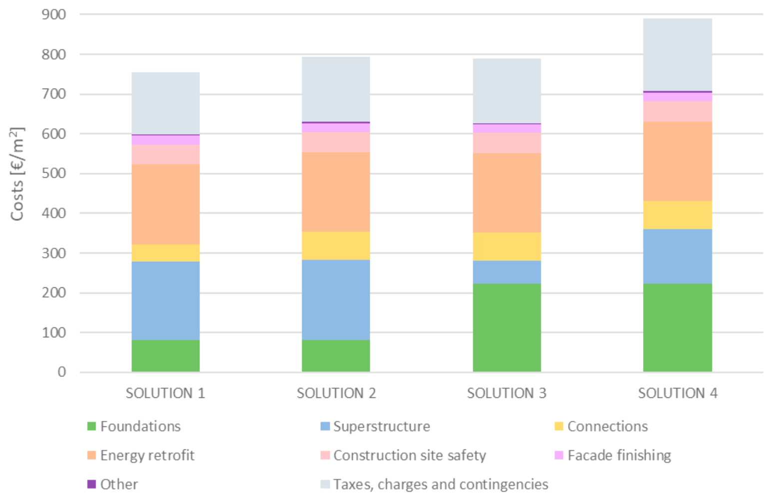

Fig. 5. Construction costs.

4.2. Life Cycle Assessment (LCA)

In order to evaluate the effectiveness of the LCT approach, i.e. the effectiveness of adopting LCT principles from an early design stage, in minimizing the impacts of a seismic retrofit intervention, a Life Cycle Assessment analysis was carried out. A LCA based on the data from Environmental Product Declarations (EPDs) was considered. Such method consists in multiplying the quantities of each material adopted in the intervention by the impact data included in the EPDs, paying attention to adopt the same functional unit. The method has two main advantages: first, it is a simple method that may be easily applied even by structural engineers, who are not LCA experts; in addition, it allows to consider impact data which are calculated for a specific product, and which are more reliable than generic data from databases. More about the adopted method may be found in Passoni et al. (2022).

Results are here reported considering 3 impact indicators: Global Warming Potential (GWP – kg CO2eq), use of Fresh Water (FW – m3), and Non-hazardous Waste Disposal (NHWD – kg). The analyses consider the sum of the impacts at the production and at the end-of-life stages, connected to the sole structural exoskeletons. In Figure 6, the results are reported in terms of total impacts and are disaggregated to show the impact of each component of the structural exoskeleton. In particular, the components are: foundations, superstructure, steel frame and ties, and connections.

Analyzing the values of total impacts, the most sustainable solution is the timber solution for all indicators except for the waste production, where the diagrid solution is slightly better. In addition, shell solutions always outperform the wall solutions. Considering the components of the structural exoskeleton, it may be observed that the impact of connections, steel frame and ties on the total impact is almost zero. On the other hand, the role of foundations is critical, and this is mainly related to the extensive use of concrete in the construction of piles (especially in the wall solutions – Sol. 3 and 4) and of the foundation curb. Solutions which minimize the impact of foundations and concrete consumption should therefore be favored and studied. Applying LCT principles to further increase the rate of reuse of elements at the end of their life would also reduce total impacts. The adoption of reused material, on the other hand, would allow for lower impacts in the production phase.

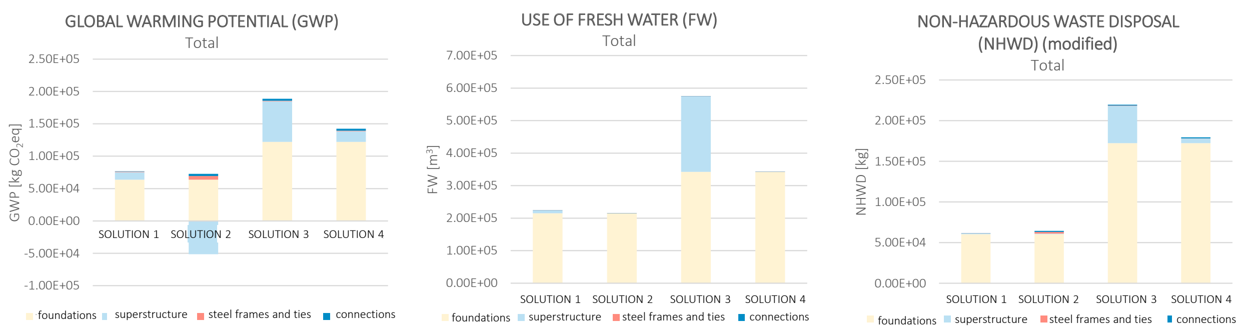

Fig. 6. LCA analysis results.

5. Concluding remarks

Four iso-performance retrofit solutions for a residential building were developed and described; all the considered structural solutions were then coupled to the same energy recovery intervention. After the retrofit intervention, the building energy class shifts from E to A1, and the seismic class from C to a A+. The solutions have been conceived in compliance with Life Cycle Thinking principles: they are carried out from the outside of the building, thus avoiding the relocation of the inhabitant; they are designed to minimize impacts throughout their life cycle. The structural design allows to control the damage on structural and non-structural components of the building, to not compromise the functionality of the building and to minimize repair costs in the case of an earthquake. With the aim of ensuring an effective comparison of the different techniques, all the solutions were designed targeting the same structural performance (life safety limit state iso-performance solutions). In particular, to avoid damage to non-structural elements, a design drift target equal to 0.3% was considered. Comparative assessments were made in terms of impacts on the retrofitted building life cycle.

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