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The LCT Challenge: Defining New Design Objectives to Increase the Sustainability of Building Retrofit Interventions

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Abstract: The decarbonization of the construction sector, which is one of the most impactful sectors worldwide, requires a significant paradigm shift from a linear economy to a circular, future-proofed and sustainable economy. In this transition, the role of designers and structural engineers becomes pivotal, and new design objectives and principles inspired by Life Cycle Thinking (LCT) should be defined and included from the early stages of the design process to allow for a truly sustainable renovation of the built environment. In this paper, an overview of LCT-based objectives and principles is provided, critically analyzing the current state of the art of sustainability and circularity in the construction sector. The effectiveness of applying such design principles from the early stages of the design of retrofit interventions is then demonstrated with reference to a case study building. Four seismic retrofit alternatives made of timber, steel and concrete, conceived according to either LCT principles or traditional, were designed and compared to a demolition and reconstruction scenario on the basis of five common environmental impact indicators. The indicators were calculated adopting simplified LCA analyses based on Environmental Product Declarations (EPDs), considering the product and End of Life stages of the building. The results of the comparative analyses confirm that LCT-based retrofit solutions are less impactful than both the traditional seismic retrofit interventions and the demolition and reconstruction scenario.

Keywords: Life Cycle Thinking (LCT); LCT-based design; sustainable building renovation; seismic retrofit interventions; comparative life cycle assessment (LCA) analyses; Environmental Product Declaration (EPD)

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1. Introduction

The ambition of global carbon neutrality by 2050 requires a vast intervention on the existing building stock, especially in Europe, where existing buildings are expected to remain in use for several decades still (for instance, it is foreseen that 85% of the existing building stock will still be standing by 2050 [1]). Buildings are globally responsible for 17.5% of Greenhouse Gas (GHG) emissions due to their operation (heating, cooling, lighting, etc.) [2]. To achieve decarbonization of European buildings by 2050, a BPIE report (2020) [1] envisions a 60% reduction in building emissions by 2030, requiring an increase in the current renovation rate from about 1% to 4.4%.

However, when considering the renovation of the existing building stock, the energy use during their use and operation is not the only source of environmental impacts, which also arise from possible damage, repair and reconstruction due to natural hazards [3]. In areas of high seismicity, the additional annual equivalent CO_2 emissions due to repair actions may even equal the annual operational emissions after thermal refurbishment [4]. In addition, social impacts connected to possible casualties and to the destruction of a built environment can be devastating, even if difficult to quantify. To account for these impacts, a wider definition of sustainability has thus been coined, also including the concepts of

safety and resilience. First defined by the 'Safesust roadmap' in 2015 [5], this enlarged concept of sustainability in the existing building sector was also included among the 17 UN Sustainable Development Goals (SDG), as 'making cities and human settlements inclusive, safe, resilient, and sustainable' [6].

It should also be considered that the emissions during building operation, either connected to energy consumption or to natural hazards, are not the only impacts associated with the construction sector. All the $kgCO_2eq$ emitted during the production of construction materials, called 'embodied carbon emissions', as well as during the end-of-life phase, represent a great share of total global emissions. Approximately 24% of global emissions are due to energy use in industry, including impacts by mining and quarrying, transportation, and construction. Considering the main construction materials, 7.2% of global emissions are due solely to the iron and steel industry, while an additional 3% is due to cement production [2]. In both cases, emissions are connected to both energy use and to the chemical reactions stemming from the manufacturing of steel and cement, which are very difficult to avoid. Besides GHG emissions, the construction sector is responsible for 50% of raw material depletion (especially sand, gravel, etc.) and for 35% of waste production [7]. In Europe, construction and demolition (C&D) waste is the largest waste stream in terms of mass, which may also include hazardous waste [8]. In such a scenario, the sole reduction of energy consumption during building operation is not sufficient to guarantee a transition towards a low-carbon society, and measures aimed at increasing building resilience and reducing or avoiding embodied carbon emissions should also be envisioned.

A Life Cycle Thinking perspective is thus required to achieve true sustainability in the construction sector and to align with the ambitious decarbonization target. As defined by UNEP/SETAC [9,10], Life Cycle Thinking (LCT) is a holistic approach, examining the impacts of a product from raw materials through to final disposal (i.e., "from cradle to grave"). In the construction sector, LCT allows for the consideration of environmental, economic and social performances in different life cycle stages of buildings and to take decisions aimed at minimizing impacts throughout their life cycle [11].

When applied to building design, LCT may be operationalized either by quantitatively estimating impacts through life cycle tools at the end of the design process or by adopting LCT-inspired design principles at an early stage of the design [9,10]. Life cycle tools are aimed at measuring and monitoring impacts in each building life cycle stage, allowing the identification of the worst and the best performing solutions on the basis of quantitative indicators [9]. Four different tools are usually adopted: (Environmental) Life Cycle Assessment (E-LCA) evaluates potential impacts on the environment, Life Cycle Costing (LCC) assesses costs, Social Life Cycle Assessment (S-LCA) examines the social consequences, and Life Cycle Sustainability Assessment (LCSA) tries to combine all the previous tools [10]. These tools allow for a quantitative calculation of the impacts of a product or a system; however, they are usually adopted only at a late stage of the building design, when details of the project are available and, usually, cannot be changed. On the other hand, LCT may also be adopted at a preliminary stage of the design of a building, by considering some LCT-based design principles that allow designers to make sustainable design decisions [11]. For example, when considering the design of retrofit interventions on existing buildings, a pre-screening of the possible retrofit alternatives according to such LCT principles may be carried out prior to the proportioning of the interventions, in order to avoid the design of unsustainable solutions [12].

Comparing these two different approaches (Figure 1), it may be observed that, when the sole life cycle tools are adopted (Figure 1a), alternatives (A1–A4 in Figure 1) may be compared only in relative terms among themselves; however, such alternatives may be very impactful in absolute terms. This could be avoided by defining some threshold values for different impact indicators, in order to have a reference to define the actual sustainability of a solution. In case of building sustainability, studies have thus recently been developed to define some benchmarks for typical reinforced concrete (RC) or mixed RC/steel buildings [13], among others. As a drawback, comparability of results from

different life cycle analyses, especially of entire buildings, may be limited due to the relevant number of assumptions required in the process (in terms of system boundaries, database selection, etc.). Some research is also under development to try to anticipate the adoption of life cycle tools at earlier stages of the design, even combining them with Building Information Modelling (BIM) technologies [14,15]. On the other hand, the adoption of LCT principles at the early stage of the design (Figure 1b) would allow for a pre-screening of alternative solutions, which may be directly discarded when not compliant with the LCT perspective (A1, A3 in Figure 1), or would allow the definition of new LCT-based alternatives (A5, A6 in Figure 1), thus leading to the design and comparison of solutions that are thus intrinsically sustainable [12].

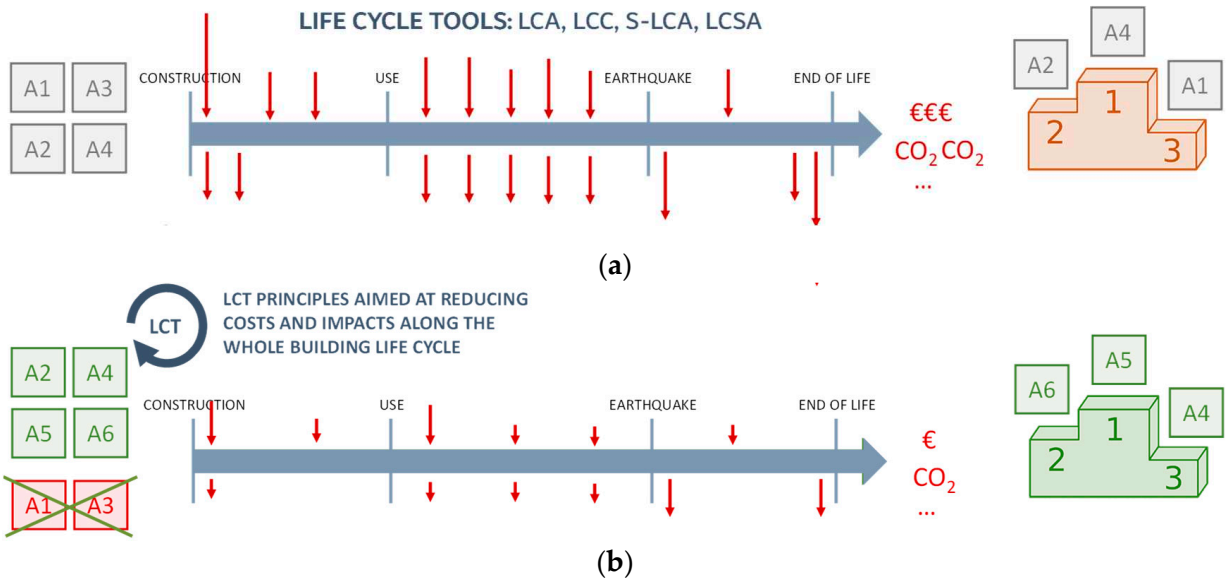

Figure 1. Conceptual differences between sustainable design approaches based on: (**a**) the ex-post evaluation of alternative solutions (A1–A4) adopting life cycle tools, and (**b**) the ex-ante adoption of a life cycle approach, defining LCT principles to discard unsustainable alternatives (A1, A3), to define new LCT-based alternatives (A5, A6), and to select and design the most sustainable ones.

Adopting an LCT approach for building design represents a significant challenge for the construction sector, since it requires a completely new mindset and new responsibilities for each stakeholder of the building value chain. In particular, the role of structural engineers would become pivotal in defining solutions that allow for the minimization of impacts along the whole building life cycle. Considering the structural design of buildings or building retrofit, the traditional performance-based design methodology should thus be enlarged by including performances related to LCT, i.e., aimed at reducing impacts at each stage of the building life, also considering potential impact trade-offs among different life cycle stages. The inclusion of all these LCT-based performances and principles in the structural design would lead to a redefinition of the concept of Life Cycle Structural Engineering (LCSE).

In this paper, the LCT-based design performances (or design objectives) to be included in the early stages of the structural design are first defined; then, possible LCT principles able to fulfill those performances are identified through an analysis of the current state of the art. The life cycle approach to renovation is subsequently applied with reference to an existing RC building, typical of the post-World War II European building stock, in order to show the potentialities and weaknesses of an LCT-based design with respect to a traditional approach for the design of building retrofit interventions.

2. LCT Approach for the Design of Building Retrofit Interventions

Redefining Life Cycle Structural Engineering (LCSE) in accordance to LCT requires a thoughtful review of all the possible impacts that can occur during a building life cycle, the definition of LCT principles to be adopted as design objectives, and the individuation of possible LCT-based design choices and strategies aimed at mitigating impacts thanks to a precautionary sustainability-oriented life cycle design.

For the definition of LCT principles and design choices, a robust definition of the building life cycle should first be provided. According to EN 15978 [16], the reference code for sustainability of construction works at the building level, the life cycle of a building may be divided into four main different stages (Figure 2). In addition, to include losses and impacts connected to hazards such as earthquakes, phases B3, B4, and B5 should also consider the presence of possible hazard risks [12] (an extensive review of the integration of seismic loss estimation in life cycle assessment is provided in Hasik et al. [17]).

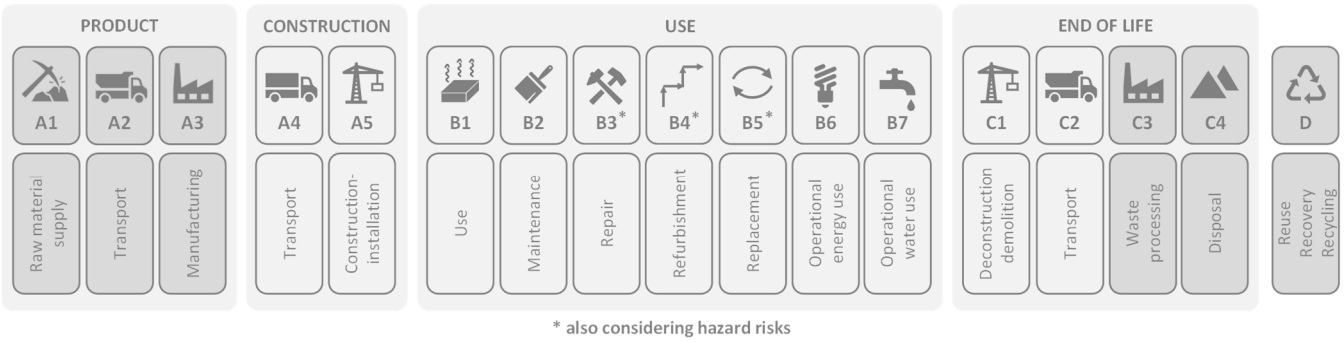

Figure 2. Building life cycle stages (adapted from UNI EN 15978) (the stages considered in the case study are those in dark grey).

The need to avoid or minimize all the potential impacts along a building life cycle leads to the definition of new sustainable LCT-based design objectives that, when set at an early stage of the design, guide the design and the choice of the best retrofit solution (Figure 3). Considering the product stage, a great share of global GHG emissions and water consumption is due to the extraction and manufacturing of construction materials—especially concrete and steel [18]. Furthermore, extraction is responsible for raw material depletion, which, due to the growth of the population and of the construction sector, is considered unsustainable in the long term, given the non-infinite material resources on our planet [19]. At this stage, a thoughtful choice of eco-efficient materials should thus be pursued. At the construction stage, easy assemblage of components should be preferred to reduce time, costs, and impacts of the construction works, such as dust and air pollutants. The impacts connected with transport of materials to the construction site should also be minimized. As for the use stage, eco-efficiency, indoor quality, comfort, and safety and resilience, especially against natural hazards, should be guaranteed. Furthermore, materials and techniques should be selected and conceived to allow for easy reparability, durability and maintenance, and adaptivity and flexibility. Finally, at the End of Life, impacts may be reduced by designing for deconstruction, recycle and/or reuse of materials and components. In addition, since the renovation of the existing buildings is considered urgent for the achievement of carbon neutrality, retrofit solutions should be conceived and designed to improve feasibility and to overcome the major barriers to renovation, especially the relocation of inhabitants, thereby encouraging public administrations and private owners to renovate their assets [20].

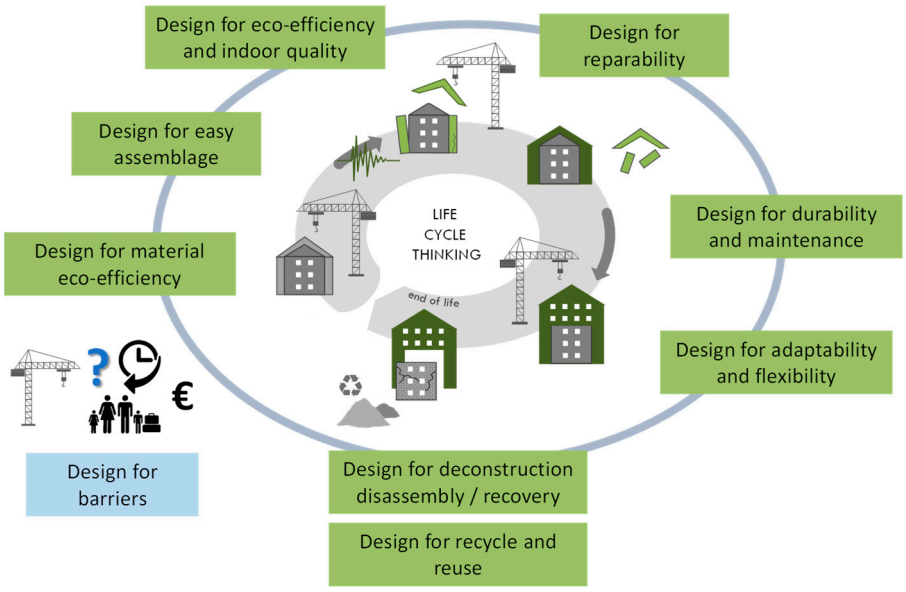

Figure 3. New LCT-based design objectives for the design of sustainable retrofit interventions of existing buildings (adapted from Marini et al. [20]).

Although many of these objectives have been individually explored by various studies, projects and regulations as possible strategies to increase the sustainability of the building sector, very few studies collected all these issues into a comprehensive ex-ante life cycle approach for the conception and the design of retrofit interventions [12]. Among others, the European EFIResources project [13], launched in 2016, focused on the development of a performance-based approach for sustainable design, enabling the assessment of resource efficiency of buildings, in the early stages of building design, and supporting European policies related to the efficient use of resources in construction; however, this aim was pursued by defining a new simplified LCA method and providing some benchmark data for the LCA of RC and mixed RC/steel buildings. Huang et al. [11] provide some LCT principles to mitigate environmental impacts of building materials, but do not consider the enlarged concept of sustainability that also includes safety and resilience. Cost Action C25 [21] addresses the concepts of design for eco-efficiency, durability and maintenance, deconstruction and reuse with reference to structural performances of buildings and infrastructures over time, first introducing the definition of Lifetime Structural Engineering. The new European framework Level (s) for sustainable buildings [22] allows for the inclusion of sustainability objectives from an early stage of the design (level 1), but, similarly to green building rating systems, it is quite a rigid framework, which does not allow one to consider specific needs of stakeholders or regions (for example, the same indicators potentially apply to areas prone to earthquakes, flood, or drought, thus overlooking the possible impact variations from one region to another). Many other studies focus just on one of these design objectives, without adopting a comprehensive approach and without evaluating possible trade-offs among life cycle stages: eco-efficient material choices [23–25]; design optimization to reduce environmental and economic impacts [26,27]; circular economy in the construction sector [28,29], or design for deconstruction/disassembly [29–31]; design for flexibility and adaptability [29,30]; reuse of structural elements [32–34], particularly of steel [35–37] and timber [38,39] structures; RC aggregate recycling [40]; advantages and drawbacks of prefabrication [41,42], etc.

In the following, an overview of the main design choices and strategies available to enhance the sustainability of buildings from the early stages of design is presented, possible trade-offs and drawbacks are evaluated, and the possibility to combine more than one strategy to achieve the new LCT-based design objectives is addressed. Principles are presented at material, construction technique, and strategy levels. A schematic representation

of the principles is provided in Figure 4, where all the possible advantages and drawbacks in terms of reduction of impacts and overcoming of barriers are shown with reference to each building life cycle stage. In this overview, only environmental issues are discussed; however, trade-offs between other pillars of sustainability—economic and social—might also be relevant.

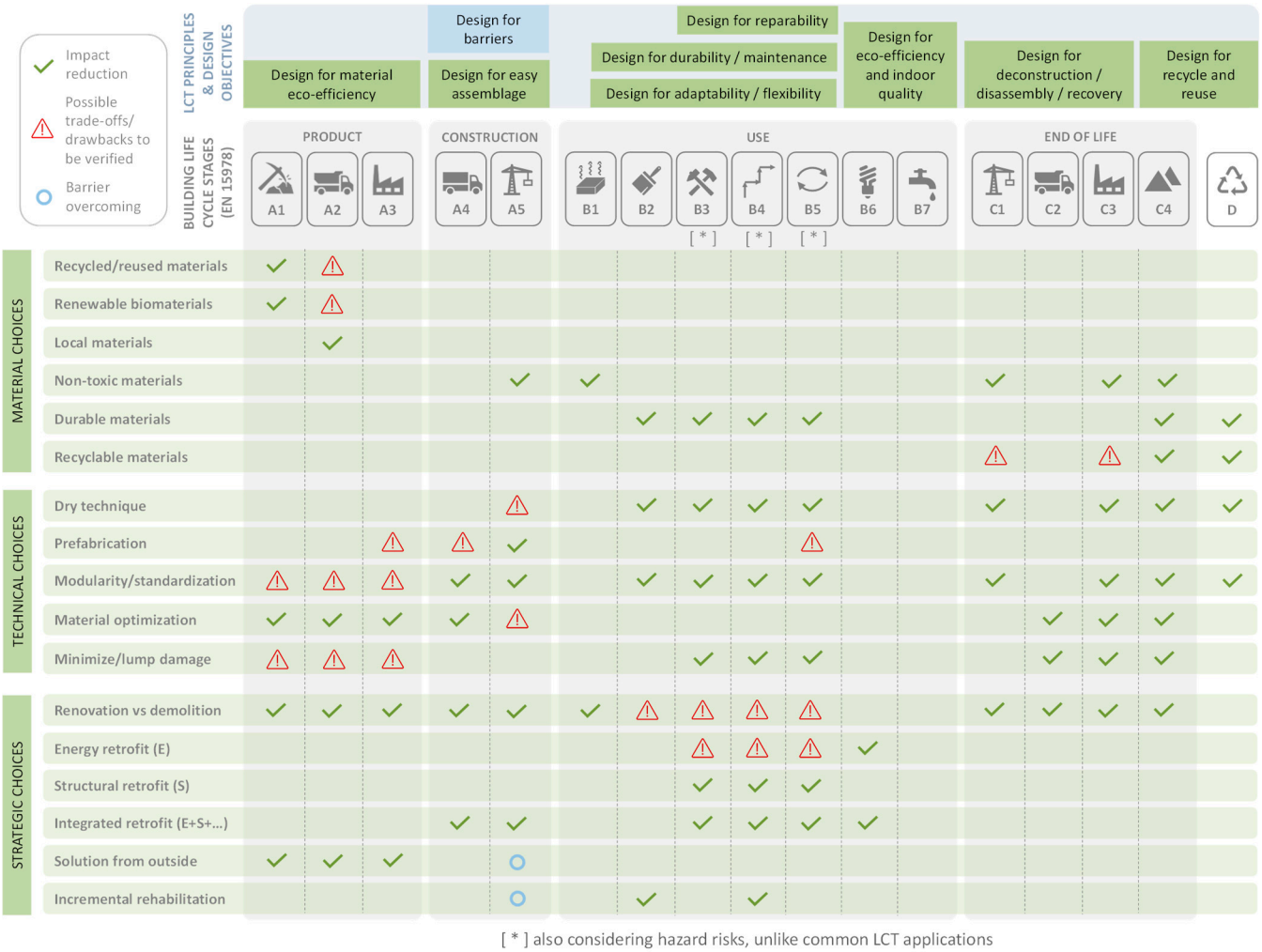

Figure 4. LCT principles for the conception and design of sustainable retrofit solutions: benefits and possible trade-offs in the different life cycle stages of a building.

2.1. LCT-Based Design Choices and Strategies at the Material Level

In order to reduce impacts connected to the extraction of construction materials (A1), the first strategy may be the adoption of recycled/reused materials or renewable biomaterials, especially fast-growing materials such as straw, hemp or bamboo [25]. In both cases, the extraction of raw material is avoided or limited; however, some differences lie in the impacts connected to material production: in the case of recycled material, some impacts may be generated for its collection and transformation; in the case of reused material, emissions may be connected to the dismantling and re-processing phases; finally, in the case of renewable biomaterial, such as timber, impacts may be connected to its collection. However, in this latter case, temporary negative emissions may be considered, since biomaterials are able to sequestrate CO_2 from the environment during their growth and store it during their building life. An additional strategy to reduce impacts during the production stage is thus the selection of local materials, reducing transport distances and fossil fuel consumption for the transportation of raw materials to production plants (A2).

Considering the use stage, potential toxic emissions caused by constructions in use (B1) should be avoided by adopting non-toxic materials. This would also imply the reduction of potential polluting emissions during the construction (A5) and deconstruction/demolition phases (C1), during possible incineration (C3), or in landfill (C4). In addition, durable materials which do not require frequent maintenance, repair, refurbishment, and substitution (B2–B5) should be preferred. The durability of construction materials and possible strategies to increase their life cycle, minimizing maintenance intervention (through the concepts of adaptability and flexibility), is covered in many studies and research [21,22,29,30], among others.

Finally, when considering the whole life cycle of a building, impacts connected to the end-of-life stage should be considered. To this aim, in line with the principles of the circular economy, the adoption of recyclable and, most of all, durable and reusable materials would allow the reduction of raw material depletion and waste production [32]. Of course, when recyclable/reusable materials are adopted, it would be better if they were combined with construction techniques that allow ease of dismantling and selective deconstruction (e.g., adoption of small and standardized elements, easily demountable connections, etc.), in order to maximize the recycling/reuse rate (this operation may require major attention during demolition operations, but impacts may be reduced if the techniques were designed for deconstruction) [29,30], among others.

In general, two main issues should be kept in mind when considering recyclable/recycled materials. Firstly, not all materials can be fully recycled; this is the case for concrete, which may at most be reused as recycled aggregate or in backfilling or downgraded casting (e.g., as road base layers). Hence, concrete recycling does not avoid the impacts connected to cement production, which is the major hotspot in concrete production [13], and should thus be reduced with other more effective strategies [43]. In addition, recycling processes may require much energy, thus not providing benefits in terms of GHG emissions, but only in terms of reduction of material extraction and waste production [32].

A comprehensive approach to building material circularity is presented in the EU Horizon 2020 BAMB (Buildings as Material Banks) project (https://www.bamb2020.eu/, accessed on 3 June 2022), addressing the topics of material passports, reversible building design and circular building assessment, among others.

2.2. LCT-Based Design Choices and Strategies at the Construction Technique Level

Another important contribution to reduce GHG emissions and the material and waste streams connected to the construction sector is the adoption of LCT-based principles for the conceptual design of new construction techniques.

The use of dry techniques may be useful in the case of maintenance, repair, refurbishment and replacement, and at the end-of-life stage. If properly engineered, it allows for complete deconstruction, separation and substitution or reuse of the elements. This may be reached, for example, by adopting bolted joints, by avoiding composite materials or wet secondary finishes, or by separating structures from claddings [30]. As a drawback, these systems may require higher time, costs, and energy for their installation, as well as higher precision in the design and production of the elements.

Prefabrication of preassembled components may be adopted to reduce time and emission during the construction operations; however, it would require more complex operations for the production of the elements, and, especially in case of macro-prefabrication, transportation to the construction site, and replacement of the elements may also become an issue [41,42]. Issues connected to the handling of off-site preassembled elements may also be an issue for deconstruction and reusability [30].

Modularity and standardization of elements and connections, minimizing the number of components and enhancing their interchangeability, is another efficient strategy to reduce waste and facilitate operations during construction, maintenance and deconstruction [30,32]. In addition, it also allows for re-usability of the elements beyond the building End of Life, especially when coupled with other choices such as micro-prefabrication and the adoption

of dry techniques. On the other hand, the need for standardization may increase impacts at the production stage, since it is in contrast with the principle of material optimization.

Material optimization is a strategy that prompts designers to reduce materials to their bare minimum, according to construction codes, avoiding surplus and standardization of elements. Especially in the design of structures, this strategy may lead to a reduction in material consumption, and consequently in the related impacts [22,26,27]; however, this principle is in contrast with the previous one, and a trade-off must be found during the design process.

Finally, when natural hazards are considered, construction systems may be designed for minimizing possible damage, adopting stricter structural design targets, and/or for lumping the damage into sacrificial structural fuses, which allow for ductile collapse mechanisms and which may be easily replaced after the hazardous event [20,44–46]. In the former case, this principle may be in contrast with the principle of material optimization, since higher dimensions of the structural elements could be required. Hence, also in this case, a trade-off between the two principles needs to be found in order to ensure the minimization of environmental impacts and costs.

2.3. LCT-Based Design Choices and Strategies at the Planning Level

At a more general planning level, some other LCT-based strategies may be adopted to enhance sustainability of the building renovation project. Firstly, stakeholders should choose between demolition and reconstruction or renovation. From an environmental point of view, renovation avoids all the impacts connected to the demolition of the existing building and to the construction of a new building, which requires greater emissions than renovation; on the other hand, it may be expected that, from a technological viewpoint, a new building requires fewer interventions of maintenance and repair with respect to an existing retrofitted building. In addition, some other issues should be considered in such a choice: economic issues, given that in some cases demolition may be more convenient, especially when deep renovation works are required; technical issues, considering that the structural capacity of existing buildings may be compromised by heavy structural decay [47]; and social issues, given that demolition of a building always requires relocation of its occupants, which is acknowledged as the first barrier to the renovation of buildings [48]. Advantages of renovation against reconstruction are also discussed in Hasik et al. [49] and in Dunant et al. [36], among others.

Then, the type of renovation should be chosen, which may be uncoupled or integrated. In the former case, a sole energy intervention is able to reduce strongly the environmental impacts connected to the building operation, which is one of the major causes of emissions, but is not able to prevent damage, or even collapse of the building, in case of possible hazards such as earthquakes; on the other hand, a sole structural intervention would maintain the GHG emissions of the existing buildings, which must be reduced by at least 60% in the next 10 years [1]. An integrated solution would instead benefit from the advantages of the two uncoupled solutions, and, in addition, may reduce costs and impacts at the construction stage, thanks to an optimization of the construction site [20,45]. A review of possible integrated structural and energy upgrading retrofit interventions may also be found in Menna et al. [50].

Finally, some strategies may be adopted to increase both the sustainability and the feasibility of the retrofit interventions, thus overcoming some of the major barriers to the renovation. Applying a retrofit solution from the outside of the building would avoid occupants' relocation, but also reduce demolition of internal finishes, thus reducing the raw material and waste streams [20,44–46,51]. Incremental rehabilitation, instead, is a strategy that allows one to distribute retrofit actions in time, combining them with programmed maintenance interventions, as long as each step increases the performances of the building with respect to the previous one. This allows a reduction in the impact of the second major barrier, which is the economic barrier connected to the construction cost [52–54].

All these LCT principles, when adopted at an early stage of the design, allow for the selection and design or reengineering of sustainable construction techniques, especially when coupled together. An example of a combination of these principles is presented in Zanni et al. (2021) [46], where a holistic (seismic, energy and architectural) retrofit intervention from the outside, inspired by LCT principles, was designed and applied to a real case study.

3. Analysis of Alternative Seismic Retrofit Scenarios for a Case Study Building Adopting EPD-Based LCA Analyses

In order to validate the effectiveness of the LCT approach in enabling the design of sustainable interventions, alternative techniques for the retrofit of an existing building were compared in terms of environmental impacts, calculated by adopting a Life Cycle Assessment (LCA) analysis based on Environmental Product Declarations (EPDs) [55].

3.1. EPD-Based LCA Analyses and Methodology

Life Cycle Assessment (LCA) is an LCT tool for the evaluation of the environmental impacts of a product or a system along its life cycle. LCA is standardized by ISO 14040:2006 [56] and ISO 14044:2006+A1:2018 [57] for general products, and by EN 15978:2011 [16] at the building level. According to these standards, an LCA analysis is divided into four steps: 1—Goal and scope statement, setting the functional unit (defined as a quantified description of the performance requirements that the product system fulfils), the system boundaries (defined as the boundaries between the product studied in the analysis and the surrounding systems, e.g., parts or processes of a technological system, time horizon, etc.), and the assumptions of the study; 2—Life Cycle Inventory (LCI), defining the relevant inputs and outputs of a product system; 3—Life Cycle Impact Assessment (LCIA), translating LCI results or indicators into environmental impacts; and 4—Interpretation of the results.

There are several studies applying the LCA tool for the comparison of different structural systems [23] or single LCT principles, such as waste management [40], prefabrication [41], elements or material reuse [32–38], etc., but, at most, they carry out ex-post LCA evaluations of solutions (see Figure 1a), without stressing the importance of applying a wider LCT approach at an early stage of the design.

In addition, the previous studies often consider general data, introducing some uncertainties about the consistency and the representativeness of the results. Adopting general data for LCA analyses means referring to general inventories, such as Ecoinvent (https://ecoinvent.org/, accessed on 3 June 2022), which may be non-representative of the materials adopted (because the data were calculated in different countries or by adopting different processes or energy mix); on the other hand, adopting specific data means referring to the exact product or component implemented in the project. A source of specific data is represented by the Environmental Product Declarations (EPDs)—or Type III Label—Introduced by ISO 14020:2011 [58] and ISO 21930:2017 [59], and regulated for construction products by EN 15804:2012+A2:2019 [60]. EPDs are voluntary labels, produced by manufacturing companies and verified by third party associations, which report the LCA results of a product, considering specific data from the manufacturer and referring to its specific production process (as required by the International Reference Life Cycle Data (ILCD) System [61]).

EPD-based LCA is a simplified procedure (as opposed to more articulated methodologies such as, e.g., [62]) for the evaluation of environmental impacts, which consists in multiplying Bill of Materials (BOM) quantities of each retrofit intervention by the impacts directly reported into specifically selected EPDs.

In this paper, the following approach for the comparison of alternative seismic retrofit solutions was followed:

1. Description of the case study building (Section 3.2);
2. Analysis of the building's structural vulnerabilities and deficiencies by carrying out nonlinear static finite element analysis, and design of alternative iso-performance seismic retrofit solutions according to building codes [63] (Section 3.3);
3. Estimation of the environmental impacts for each solution by means of EPD-based LCA analyses (Section 3.4): definition of goal and objectives of the LCA analysis (Section 3.4.1), definition of scope and system boundaries (Section 3.4.2); computation of the Bill of Materials for each alternative resulting from the structural design (Appendix A); selection of the EPDs from Italian/European databases (Appendix B); definition of calculation assumptions and choice of impact category indicators (Section 3.4.3);
4. Analysis and critical discussion of the results (Section 4).

3.2. Case Study Building

The case study building is an infilled RC structure built in 1970 in Brescia, a city in northern Italy characterized by medium/high seismicity (ag = 0.161, Zone 2, NTC 2018) [63] and a mild climate (2.265, Zone E, DPR 412/93) [64]. The building was actually retrofitted through the employment of an exoskeleton, aimed at an integrated improvement of both structural and energy performances. Such intervention was taken as a reference to design possible alternatives that have the same structural performance (iso-performance), but implement different LCT principles and adopt different structural materials [65].

The building is composed by two rectangular units connected in correspondence to the staircase well, with an L-shaped plan of about 230 m^2 per floor (Figure 5). The first unit, herein referred to as 'building A', has plan dimensions equal to 12.28 m × 8.12 m and inter-story height equal to 3.06 m on the ground floor and 3.15 m on the upper floors; the second unit, herein referred to as 'building B', is located over a 1.05 m-high RC basement, it has plan dimensions equal to 13.60 m × 9.80 m and inter-story height equal to 3.10 m on the ground floor and 3.95 m on the top floor. The building thus presents relevant irregularities in both plan and height.

Figure 5. Case study building composed by units 'A' and 'B': perspective drawing and plan (**top**); pictures of two prospects (**bottom**) (adapted from [65], ©Di.mo.re. Srl).

The structural system of both units consists of three longitudinal and two transversal one-way RC frames (founded on either shallow pads or beams) designed for gravity loads only. The staircase well is made of RC walls with 25 cm thickness, and was also not designed to withstand horizontal loads, laid on an independent beam foundation. The floor slabs consist of one-way RC beams and hollow clay blocks with a 3 cm concrete topping, for a total thickness of 19 cm. The outer frames are infilled with masonry panels made of two layers of hollow blocks with a 7 cm inner cavity and three layers of plaster, except for the balconies and the porch on the ground floor entrance of building A. Further details may be found in Labò et al. [65].

3.3. Seismic Vulnerability of the Case Study Building in the As-Is Condition and Design of Iso-Performance Seismic Retrofit Alternatives

Nonlinear static analyses adopting the N2 method [63,66] were carried out with the Midas Gen (2020) software [67] to assess the reference building's seismic vulnerability. Due to the presence of the stairwell at the intersection of the two units, to better identify the building unit interactions, three different Finite Element Models (FEM) were developed: the whole building, building A alone and building B alone. In each model, the frame structural members were modelled through the use of beam elements with end plastic hinges (whose backbone curves were defined using the flexure and shear capacity models suggested in Eurocode 8) [68]. The ground-floor columns were considered to be fully fixed at their base. Infills were modelled as compression-only struts converging into the nodes, adopting the Decanini et al. [69] model, but considering d_y = 0.3% and d_p = 0.5% as cracking and peak drift, as suggested in [70]. The staircase walls were modelled as equivalent beam–column elements with bilinear plastic hinges on each floor. A rotational spring (k_θ = 320,000 kNm) was introduced at the base of the walls with a view to represent the existing foundation system flexibility. Finally, the floors were modelled as rigid diaphragms, but considering a finite ultimate capacity, which was calculated assuming a tied arch resistant mechanism according to Marini et al. [71] (in this case, the maximum allowed in plane floor action is f = 108.4 kN/m, corresponding to the development of a brittle shear failure at the joist/block interface in correspondence to the arch supports).

The building failed to comply with both the Collapse Prevention Limit State (CPLS, return period 2475 years) and the Life Safety Limit State (LSLS, return period 475 years) capacity–demand checks prescribed by the Italian building code [63] (Figure 6, left). The retrofit intervention was thus conceived to improve the seismic performances of the building. Four different iso-performance solutions were proposed, all targeting the same seismic behavior of the retrofitted building (Figure 6, right). All the solutions were designed to be over-resistant at the LSLS and dissipative at the CPLS, i.e., designed to maintain the retrofitted building's response in the elastic range for seismic demand values with a return period lower than 475 years and to develop a ductile mechanism for stronger seismic demand levels. Further details on the structural analyses of the reference building in the as-is and post-retrofit conditions may be found in Labò et al. [65].

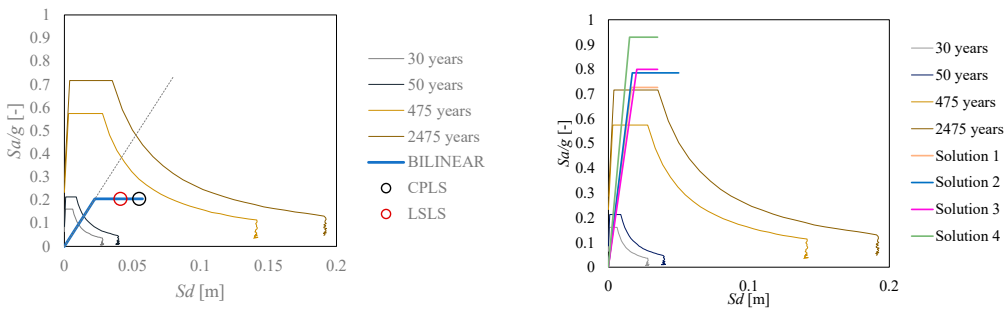

Figure 6. Equivalent bilinear capacity of the building in the as-is (**left**) and in the retrofitted (**right**) conditions compared to ADRS spectra for four different return periods (30, 50, 475, and 2475 years). (Adapted from [65]).

An additional thermal insulation layer and the architectural finishing would then allow for a complete aesthetic renovation of the building, the discussion of which is, however, beyond the scope of this paper.

All the proposed iso-performance structural retrofit solutions rely on exoskeletons, which may be completely assembled from the outside of the building to avoid occupants' relocation, and which can also be combined with energy amelioration measures and architectural upgrading interventions of the building envelope [20].

From a structural point of view, all the exoskeletons are conceived as external lateral load resisting systems (LLRS), connected to the building floors by means of continuous steel chords and ad-hoc connections along the perimeter to transfer the seismic loads from the existing structure to the new elements. Both shell and wall exoskeletons are proposed; in the former, the LLRS is made of the engineered additional continuous façades, while in the latter, it is composed of a few discrete shear walls [20,44] (Figure 7).

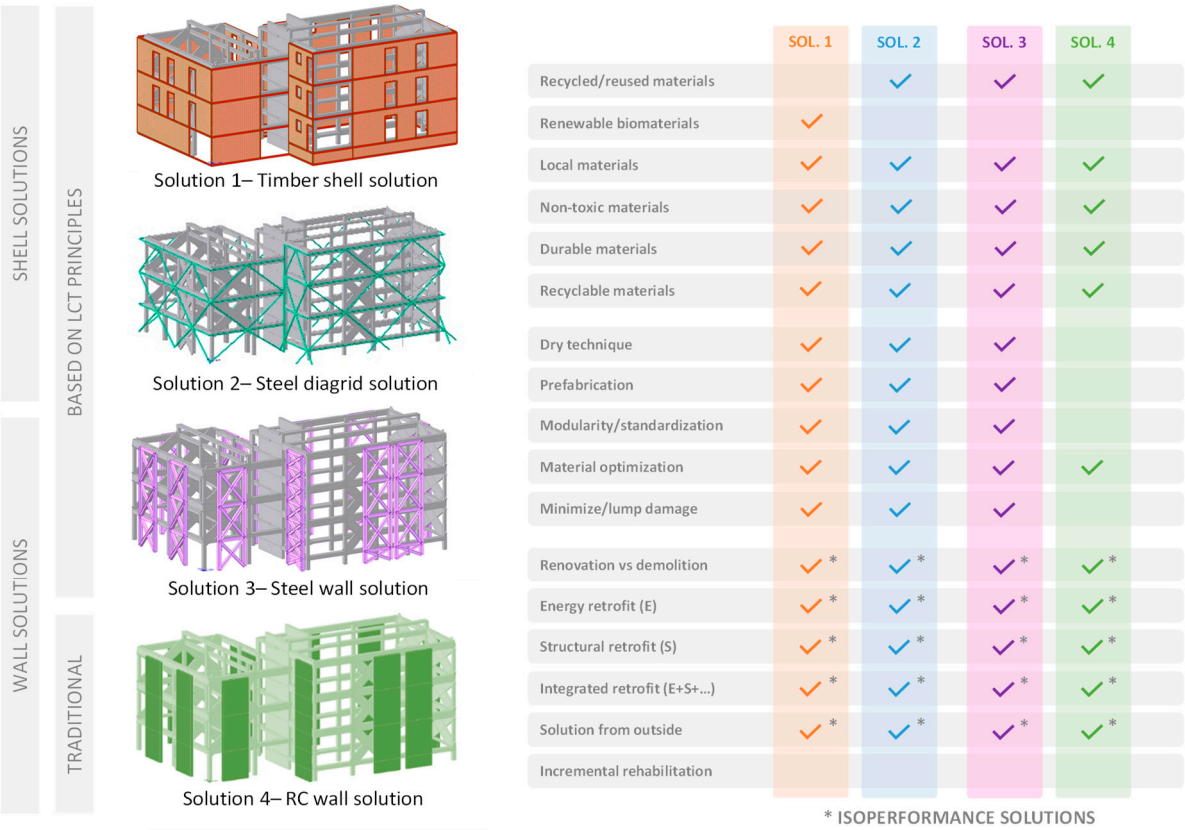

Figure 7. Alternative iso-performance structural alternatives and LCT principles considered for the design of each solution.

In regard to the exoskeleton superstructure, cross-laminated timber (CLT) (Solution 1) and tubular steel (Solution 2) are adopted for the two shell solutions, while steel profiles (Solution 3) and RC elements (Solution 4) are adopted for the two wall solutions. The two shell solutions and the steel wall solution are conceived and designed in compliance to the principles of LCT and to Eurocode 8, while the RC wall solution is conceived by considering traditional design rules and in compliance with structural codes only. The FEM structural models of the four proposed solutions are shown in Figure 7.

Solution 1 is a timber shell exoskeleton made of CLT panels. According to the LCT principles, the exoskeleton is made of a renewable biomaterial, which may be recycled/reused at the building's end of life. The solution is a prefabricated dry technique, adopting modular elements and standardized connections, which are conceived to concentrate the damage in case of strong earthquake action, and which may be easily replaced if needed. The

exoskeleton is entirely demountable, and the layout of the components is designed to guarantee reuse at end of life. Additional details on this LCT-based timber shell solution and its design may be found in Zanni et al. [46].

Solution 2 consists in the use of a diagrid system made of steel tubular modules spanning between adjacent floors. Diagrids are designed as shell exoskeletons composed as a discrete grid structure. Solution 3 is a more traditional steel exoskeleton featuring "shear walls" made of HEA (IPBL) commercial steel profiles. From an LCT principles perspective, these exoskeletons feature the advantage of being made of steel, which is a recycled/reused material that may also be recycled/reused at the end of life, with ease of deconstruction also being ensured. To this aim, Solutions 2 and 3 are designed as dry, prefabricated, modular and standardized. Ad-hoc connections are conceived to enhance structural disassembly feasibility and to concentrate the damage in case of strong earthquake loading, thus mitigating the possible impacts and costs in the aftermath of both mild or strong seismic events. Further details on the structural design of diagrid solutions and steel walls for the renovation of existing RC buildings may be found in Labò et al. [46], Di Lorenzo et al. [51], and Passoni et al. [44], among others.

Finally, Solution 4 is a traditional RC wall solution. With regard to the construction materials, the structure is composed of concrete, which is usually not a recycled material but may be subsequently recycled to produce concrete aggregates and steel rebars, which are made of recycled and recyclable material. Regarding the construction technique, it is a traditional cast-in-place solution, which must be demolished at the End of Life, producing waste that should be sorted to be recycled (similarly to the existing structure), with a share of the demolition waste to be sent to landfill. The connections are neither designed to allow for deconstruction, nor to concentrate damage, which will thus be spread across the walls, particularly at the base. Adopting this traditional approach, demolition of the walls may be required after strong earthquakes, thus not allowing for damage and impact minimization during the building use stage.

The exoskeletons lie on new foundations, which are made of RC beams and micropiles. The foundations of the shell and wall exoskeletons are quite different. Indeed, by exploiting the extension of the façades, the shell exoskeleton spreads the shear flow along the whole façade length and increases the lever arm of the vertical reaction forces balancing the base-bending moment induced by the seismic action, thus requiring a reduced number of micropiles; on the other hand, the wall exoskeleton concentrates the seismic resistance in a few shear walls of smaller extension, thus needing a higher number of micropiles (110 micropiles of 15 m length for Solutions 3 and 4, versus 14 micropiles for Solutions 1 and 2). For the shell solutions, a continuous RC foundation beam is, however, required along the building perimeter.

In addition, to ensure a proper seismic resistance function of the exoskeleton, diaphragms play a critical role. The maximum in-plane capacity of the existing floors in the retrofitted configuration was thus calculated to assess the potential need for their strengthening [71]; the two building units A and B were analyzed separately, given that their slabs are set at different heights. Strengthening of the floors proved to be necessary for the diaphragm action to be ensured; to this end, perimetral steel chords and additional ties in correspondence to the staircase walls are needed. It is worth noting that such strengthening intervention does not require any downtime on the use of the building.

All solutions are realized adopting local, non-toxic and durable materials, and the techniques are designed considering a balance between the principles of damage reduction and material optimization, aimed at reducing raw material consumption.

Supplementary information on the structural design and structural detailing of these interventions may be found in Labò et al. [64]. The Bill of Materials related to each solution is reported in Appendix A (Table A1).

3.4. EPD-Based LCA for the Evaluation of the Case Study Environmental Impacts

3.4.1. Goal and Objectives

Once the four iso-performance structural solutions were designed, the EPD-based LCA method was applied to evaluate the environmental impacts of each alternative. A demolition and reconstruction alternative (Solution 5) was also considered. An attempt was made to answer to the following questions with support of quantitative data:

1. Considering structural exoskeletons, which is the technology with lower environmental impacts? In addition, what are the main drivers of those impacts, among structural elements, adopted materials and life cycle stages?
2. Are LCT-based retrofit solutions more sustainable than traditional solutions?
3. Is structural retrofit more or less sustainable with respect to the demolition and renovation scenario?
4. Is LCT-based design effective in increasing the sustainability of the construction sector and of the existing building stock?

Clearly, the results of this research are not exhaustive, since they refer to a single case study, but they are proposed as a hopefully useful basis from which to initiate a critical discussion among the scientific community, as well as to plan future research developments on Life Cycle Structural Engineering (LCSE).

3.4.2. Scope and System Boundaries

In this study, only the structural system is considered for the evaluation of the environmental impacts (the same energy and architectural upgrading measures are assumed for all the proposed solutions and are thus excluded from the analyses). The structural system is composed of: 1—foundations, i.e., RC beams, micropiles made of spheroidal cast iron tubes filled with concrete, and steel connectors linking the beams to the existing foundation; 2—superstructure, i.e., CLT panels in Solution 1, steel pipes in Solution 2, steel walls in Solution 3, and RC walls in Solution 4; 3—connections, i.e., steel stringcourses and studs along the perimeter of each floor; and 4—steel ties to ensure the floor diaphragm action and, for Solution 1, steel elements reinforcing the wall openings. When RC elements are considered, the amount of concrete, steel rebars and plywood formwork is computed (Appendix A—Table A1).

For a comparison between the renovation and the demolition and reconstruction scenarios, the structural system of the existing and of the new buildings are also defined. For the existing building, the system is composed of: foundations, RC frame (beams, columns, stairs, staircase walls), floors (beam and hollow clay blocks slab system with concrete topping), roof (beam and hollow clay blocks slab system with clay tiles), and masonry infills along the building perimeter (hollow clay bricks and mortar). For the new building, the same geometry and elements of the existing building are considered with the addition of the RC walls of Solution 4. With respect to the existing structure, in the new building a slab cross-section of 24 cm + 5 cm is considered for the floors, and a welded mesh Φ6 with 20 cm × 20 cm dimensions is added to the concrete topping; as for the RC walls, RC footings and beams are considered, designed according to the current building code (NTC2018—[63]). The Bill of Materials for these scenarios is reported in Appendix A (Table A2).

As for the life cycle stages, the product stage (Modules A1–A3) and end-of-life stage (Modules C3–C4–D) are considered in the analyses (in dark grey in Figure 2). According to Figure 4, these modules are the most affected by LCT principles such as the adoption of recycled materials, of recyclable/reusable materials, and of principles allowing for easy deconstruction and for reuse/recycle of structural elements (i.e., prefabrication, dry techniques, modularity and standardization, among others). LCT principles also affect the construction stage (Modules A4–A5), the deconstruction stage (Modules C1–C2), and the stages affected by a possible earthquake scenario (Modules B3–B5); however, these modules are unfortunately still not included in EPDs and are thus disregarded in the present

study. Further development of this research would extend the evaluation of environmental impacts to include these stages also, by adopting traditional LCA analyses (e.g., [62]).

To achieve the study's goals, two different kinds of analyses were carried out considering different system boundaries (Figure 8):

1. To define the most sustainable among the considered retrofit solutions (Solutions 1–4), the environmental impacts connected to the product and end-of-life stage of the exoskeletons (foundations + superstructure + connections + ties) are compared (system boundaries shaded in green in Figure 8, top). For the timber shell and steel diagrid alternatives, different end-of-life scenarios are also discussed with reference to the superstructure, and the best scenario is then considered for the final comparison.
2. To compare the renovation (Solutions 1–4) and the demolition and reconstruction (Solution 5) scenarios, the presence of the existing building is also accounted for. In the renovation scenario, demolition of the existing building is summed to the demolition of the different alternatives at End of Life (in Modules C3–C4–D) (system boundaries shaded in grey and green in Figure 8, top). In the demolition and reconstruction scenario, the demolition of the existing building is instead considered as a preliminary action for the building reconstruction (Modules A1–A3) and it is summed to the production and demolition of the new building (system boundaries shaded in grey and blue in Figure 8, bottom). In both cases, the impacts connected to the product stage of the existing building were not considered, since the existing building was built in 1970s, and it has thus already expired its nominal structural service life (equal to 50 years according to Eurocodes [68]).

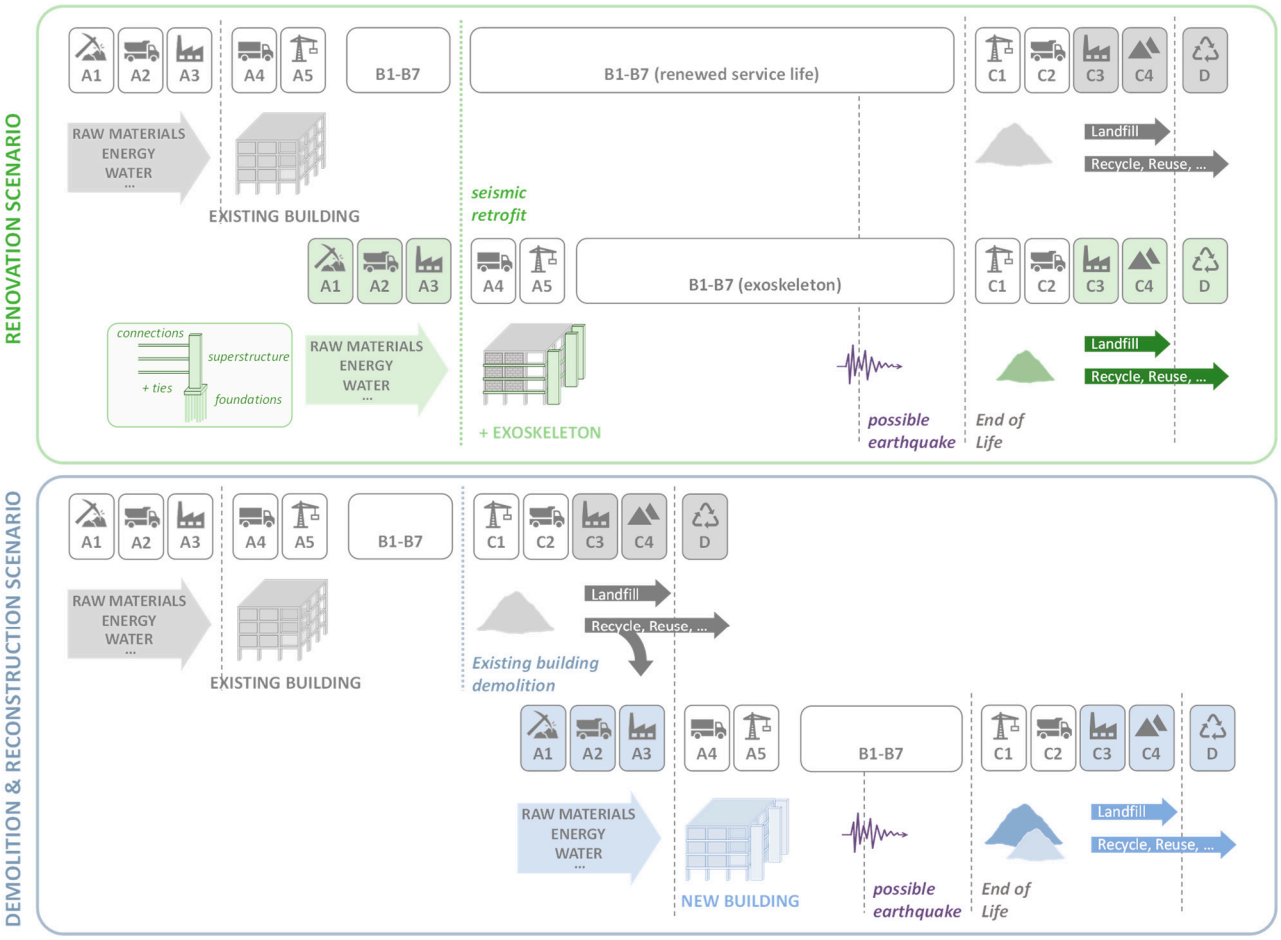

Figure 8. System boundaries and scope of the LCA for the renovation (**top**) and the demolition and reconstruction (**bottom**) scenarios.

3.4.3. Choice of EPDs, Analysis Assumptions, and Impact Category Indicators

For the evaluation of the environmental impacts with EPD-based LCA analyses, specific EPDs must be selected for each structural material, element or system included in the retrofit intervention. For the choice of EPDs, typical materials adopted in the case study building's region were selected, possibly selecting those manufacturers that are near the construction site. Local construction companies were also interviewed to select the material suppliers and manufacturers usually referred to in similar retrofit interventions. EPDs were found in the Italian database (https://www.epditaly.it/, accessed on 3 June 2022) and in the European database (https://www.environdec.com/, accessed on 3 June 2022). A list of the EPDs adopted in the case study is reported in Appendix B (Table A3), together with the adopted assumptions.

It should be noted that, in some cases, two different EPDs were selected to represent one single material, in order to account for both the product and the end-of-life stages. In the first version of EN 15804:2012, EPDs were required to include modules A1–A3, whilst all the other modules were facultative. These boundaries were expanded in the latest version of the standard EN 15804:2012+A2:2019 [60], which also requires the consideration of modules C1–C4 and D. Therefore, in EPDs published before 2019, end-of-life data are often missing. To overcome this limitation, two different EPDs were thus considered in these analyses: Italian EPDs were considered for Modules A1–A3, and, in absence of data for Modules C3–C4–D, they were taken from equivalent European EPDs and were scaled proportionally to the impacts of Modules A1–A3, i.e., adopting Equation (1):

$$\text{Impacts } (\text{C3} - \text{C4} - \text{D})_{\text{Italian}} = \frac{\text{Impacts } (\text{A1} - \text{A3})_{\text{Italian}}}{\text{Impacts } (\text{A1} - \text{A3})_{\text{European}}} \cdot \text{Impacts } (\text{C3} - \text{C4} - \text{D})_{\text{European}} \quad (1)$$

In some other cases, such as for the CLT panels or micropiles, no Italian EPDs are available to date, so reference was made to European EPDs, including data for all the modules of interest. Finally, European EPDs were also considered to develop different end-of-life scenarios, such as in the case of steel diagrids.

As for impact categories, the following five different indicators [72,73], deemed most relevant and also more easily communicated and understood by each stakeholder of the renovation process, were calculated and discussed:

- Global Warming Potential (GWP) (kgCO_2eq.)
- Consumption of renewable primary energy resources (PERT) (MJ)
- Consumption of non-renewable primary energy resources (PENRT) (MJ)
- Use of fresh water (FW) (m^3)
- Non-hazardous waste disposal (NHSD) (kg)

According to the standard EN 15804+A2 [60], the first indicator listed above (GWP) is classified as an impact category, while the other four represent environmental flows. In particular, GWP is a metric aimed at measuring the manner in which greenhouse gases absorb energy and trap heat in the atmosphere, causing a global warming effect. This indicator is measured in terms of kg of equivalent carbon dioxide, meaning that all the greenhouse gas emissions are scaled and converted into equivalent CO_2 (IPCC92 [74]). For example, it may be considered that 1 kg of carbon dioxide CO_2, 1/28 kg of methane CH_4, and 1/298 kg of nitrous oxide N_2O can be associated with the same gross additional heat input into the atmosphere in a 100-year period, although their effects are not evenly distributed over time—e.g., CH_4 is responsible for the maximum temperature change when emitted, but it is reabsorbed by the atmosphere in about 60 years; on the other hand, CO_2 absorbs less energy, but its warming effect is almost permanent over time.

Carbon sequestration and storage are particularly relevant when computing the GWP indicator. Wood and concrete are capable, in some phases of their lives, of sequestrating carbon from the environment and store it for a certain period of time. The evaluation of the amount of stored carbon, the amount of released carbon, and the time of release is still an open research issue. In the present study, the biogenic carbon content of wood is

calculated in the considered EPD (Stora Enso EPD, Table A3) according to EN 16485 and 16449 standards [75,76], assuming that carbon is instantaneously sequestrated in Module A and instantaneously released in Module C. These assumptions are consistent with the hypothesis of wood sourced from steady state and sustainably managed forests. As for carbon sequestration, more accurate models may be considered, especially when adopting dynamic LCA, where sequestration may be operated by the forests that are harvested to produce timber products (forward-looking approach) or by the forests that are replanted in substitution of the harvested ones (backwards-looking approach) [23]. As for the released carbon, the assumption of instant release at the end of life is consistent with EN 15804 [60]; however, in the case of reuse of the timber elements or in a future scenario of available carbon capture and storage technologies, the storage of carbon will last beyond the nominal timber element's end of life (a "new" life starts for the reused element, thus the actual life cycle is extended), without being released into the atmosphere. The prolongation of the life cycle of timber elements presents, however, some concerns and is still an open research issue [38].

As for concrete elements, they are capable of sequestrating carbon from the atmosphere thanks to the carbonation effect. Unlike biomaterials, which just temporarily store carbon, this should be considered an active carbon sequestration mechanism that reduces CO_2 emissions in the atmosphere during the building life cycle [25]. In the considered EPD (Beton EPD, Table A3), carbon sequestration is considered both in Module B1 (use stage) and in Module C4 (disposal), considering that 75% of the concrete waste in landfill, being crushed and exposed, is subject to carbonation.

4. Results and Discussion

Results of the EPD-based LCA analyses are herein reported and commented. The impacts at the production stage and at the end-of-life stage are first presented separately; then, the total impacts are reported, first considering the exoskeletons, and then comparing the renovation options to the demolition and reconstruction scenario.

4.1. Impacts at the Product Stage

Considering the exoskeleton alone, the impacts of the four alternative solutions at the product stage (Modules A1–A3) are compared. Results are disaggregated both considering the different components of the structural system (foundations, superstructure, connections, ties) (Figure 9i) and the different materials (concrete, steel rebars, steel profiles, steel tubes, CLT panels, plywood scaffolds and micropiles) (Figure 9ii).

For all the considered environmental impact indicators, at the production stage, the least impactful solution is the timber shell, followed by the steel diagrid, the steel walls and the RC walls. The sole exception is represented by the PERT indicator, which shows that the maximum renewable primary energy resources are consumed by the timber shell solution, in particular for the production of the CLT panels. This is probably due to the fact that CLT manufacturers usually burn wood scrap onsite to produce steam or electricity to be adopted in their production process [24]. However, consuming renewable primary energy resources is more sustainable than consuming non-renewable resources.

In regard to the GWP indicator, the timber shell, steel diagrid, steel wall and RC wall solutions are responsible for 0.21×10^5, 1.07×10^5, 1.64×10^5, and 2.27×10^5 $kgCO_2eq.$, respectively. The low value of the timber solution is due to the carbon sequestration of CLT panels (accounting for -6.98×10^4 $kgCO_2eq.$ in Module A1). In all solutions, the larger share of impacts is associated with the foundations and then the superstructure, while the contribution of ties and connections is almost negligible due to the lower material quantities. In the wall solutions, the impacts of just the foundation system (1.43×10^5 $kgCO_2eq.$) are higher than the total emissions of the shell solutions, due to the high number of micropiles required. The RC wall traditional solution is by far the least sustainable at the production stage, having a GWP equal to 1103% of the GWP of the timber shell solution, 212% of the

GWP of the steel diagrid solution, and 139% of the GWP of the steel solution, which has similar foundations but adopts a more sustainable material.

Figure 9. Environmental impacts at the product stage (Modules A1–A3) considering only the additional exoskeleton. Data are disaggregated considering the different parts of the structural system (**i**) and the different structural materials (**ii**).

Considering the disaggregation of the results by material (Figure 9ii), the impacts due to the concrete is the most relevant for all the considered solutions, since an extensive use of concrete is required by the foundation system (made of RC beams and micropiles filled with concrete). High impacts are also connected to steel tubes and profiles for

Solutions 2 and 3, to the micropiles in the two wall solutions (Solutions 3 and 4), and to the reinforcing bars in the RC wall solution (Solution 4). As for the timber shell solution (Solution 1), non-negligible impacts are connected to the steel profiles for the reinforcement of the openings (which may be unnecessary in many applications); nevertheless, these impacts are counterbalanced by the negative beneficial contribution of the CLT panels. Similar results are found for the PENRT indicator. These data highlight the attention on the low sustainability of the foundation systems made of RC beams and concrete-filled iron micropiles, thus suggesting the need for re-engineering of the foundations.

The FW indicator further stresses the above observation; concrete is the material that requires the highest use of fresh water (2.45×10^5 m^3 of water for the first two solutions, 3.47×10^5 m^3 for the steel wall solution and 6.06×10^5 m^3 for the RC wall solution). Such an indicator is expected to become more and more relevant in the years to come.

Finally, with regard to the NHWD indicator, the impacts are 3.34×10^3 kg, 3.24×10^3 kg, 5.68×10^3 kg and 6.89×10^3 kg for the timber shell, steel diagrid, steel wall and RC wall solution, respectively. The main contribution is due to the production of steel elements (rebars, diagrid tubes, and steel profiles), and of concrete and plywood in Solution 4. However, these impacts are almost negligible when compared to the production of waste at the end-of-life stage.

4.2. Alternative End-of-Life Scenarios

In order to evaluate the effects of LCT principles on the environmental impacts of the alternative solutions, different end-of-life scenarios are herein evaluated for Solution 1 (Figure 10) and Solution 2 (Figure 11). Considering the superstructure of the timber shell and of the steel diagrid exoskeletons, i.e., the CLT panels for the former solution and the steel tubes for the latter, different scenarios are assessed considering different percentages of materials for reuse, recycle, incineration and landfill.

4.2.1. End-of-Life Scenarios for the Timber Shell Solution (Solution 1)

For the timber shell solution, impacts connected to four different end-of-life scenarios (Modules C3–C4–D) were evaluated and compared to impacts calculated for the product stage (Modules A1-A3) (Figure 10). Scenario 1 envisions 90% reuse and 10% incineration; this scenario does not represent the current practice, but these percentages may be reached in future, if the deconstruction of the elements is ensured by adopting proper LCT design principles and other challenges connected to the timber value chain are overcome [38]. Scenario 2 considers 55% recycling, 44% incineration and 1% landfill, according to Hawkins et al. [23]. Scenario 3 considers 53% reuse, 18% incineration and 30% landfill, according to Liang et al. [24]. Finally, Scenario 4 is the worst-case scenario, which unfortunately can be currently found in practice, where 100% of the CLT panels are landfilled. It should be noted that, for CLT panels, potentially infinite scenarios may be built by adopting the considered EPD, which provides disaggregated data for 100% reuse, 100% recycling, 100% incineration, and 100% landfill scenarios.

The GWP indicator computation highlights the significant impacts connected to the landfill scenario. In this case, in fact, all the biogenic carbon is considered to leave the CLT elements instantaneously. The total $kgCO_2eq.$ for the product and end-of-life stages of the superstructure thus varies from -6.81×10^4 to 3.25×10^4 from Scenario 1 to Scenario 4, respectively. Considering the use of energy, the use of renewable sources increases by raising the landfill rate and reducing the reuse rate; while the use of non-renewable energy is optimized by Scenario 2, which has the maximum rate of incineration and avoids the consumption of additional non-renewable energy after the building's end-of-life. The use of fresh water (FW) is negligible for all the considered scenarios. Finally, the amount of non-hazardous waste (NHWD) is directly proportional to the rate of landfilled material.

Figure 10. Environmental impacts at the product stage (Modules A1–A3) and end-of-life stage (Modules C3-C4-D) for the superstructure of the timber shell exoskeleton (Solution 1), considering four alternative end-of-life scenarios (on the bottom right).

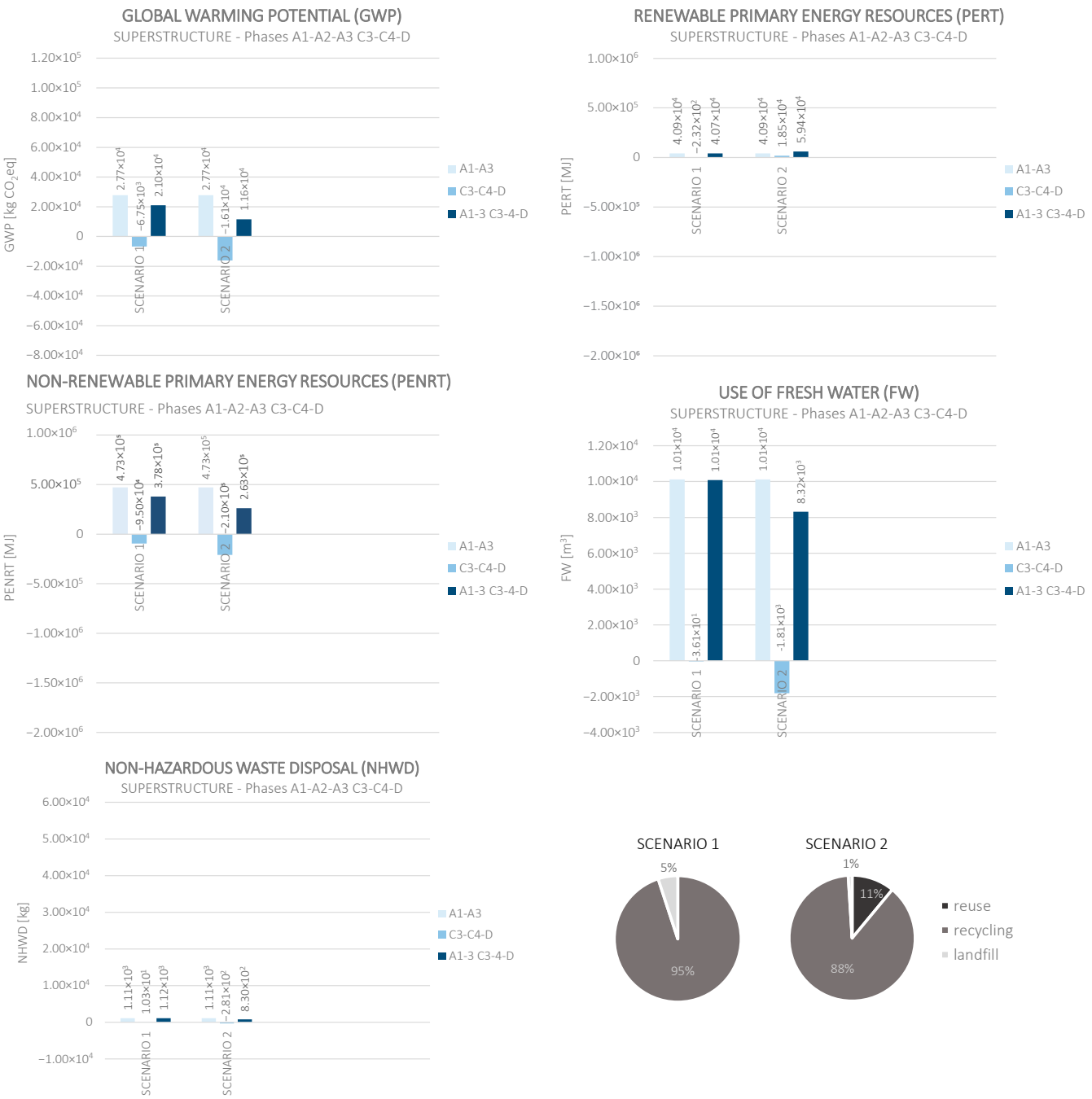

Figure 11. Environmental impacts at the product stage (Modules A1–A3) and end-of-life stage (Modules C3–C4–D) for the superstructure of the additional steel diagrid exoskeleton (Solution 2), considering two alternative end-of-life scenarios (on the bottom right).

4.2.2. End-of-Life Scenarios for the Steel Diagrid Solution (Solution 2)

For the steel diagrid solution, impacts connected to two different end-of-life scenarios (Modules C3–C4–D) were considered and compared to impacts calculated for the production stage (Modules A1–A3) (Figure 11). Scenario 1 considers 95% recycling and 5% landfill (according to ArcelorMittal EPD, Table A3), which is the most common case considered in EPDs of steel products. Scenario 2 considers 11% reuse, 88% recycling and 1% landfill, according to Del Acero EPD (Table A3). In the case of steel tubes, only two scenarios were considered, given that all the available EPDs provide impacts for a fixed scenario only. To ensure comparability of the data from different EPDs, impacts from the selected Italian

EPD (Table A3) are adopted for the product stage (Modules A1–A3), while impacts at the end-of-life stage (Modules C3–C4–D) are calculated from the two European EPDs (Table A3) and scaled considering Equation (1).

For all the considered indicators, Scenario 2 is better than Scenario 1. This is due to the reduced rate of landfilled material and to the presence of reused material, whose benefits are quantified as avoided manufacturing of structural steel hollow sections connected to potential future constructions adopting these reused elements. If higher rates of reusability were achieved through the adoption of dry techniques, standardization, easy deconstruction, etc., as envisioned by [35,36], even lower impacts may be expected for the steel solutions.

4.3. Impacts at the End-of-Life Stage

Considering just the exoskeleton, the impacts of the four alternative solutions at the end-of-life stage (Modules C3–C4–D) are compared. As already done for the product stage (Figure 9), results are disaggregated considering the different components of the structural system (foundations, superstructure, connections, ties) (Figure 12i) and the different structural materials (concrete, steel rebars, steel profiles, steel tubes, CLT panels, plywood scaffolds and steel micropiles) (Figure 12ii). For the superstructure, the best-case scenarios from Section 4.2 were considered, i.e., Scenario 1 for the timber shell solution and Scenario 2 for the steel diagrid solution. For all the indicators, end-of-life impacts and benefits connected to the micropiles are not considered, since it is assumed that micropiles are not removed from the ground at the end of life. For the NHWD indicator, the presence of micropiles in the ground is either neglected (scenario 'a' in the indicator NHWD of Figure 12) or considered (scenario 'b' in the indicator NHWD of Figure 12) as waste, assuming in the latter case a 0% recycling/reusing rate for both the micropiles and the filling concrete.

It may be observed that, with the exception of NHWD, all the impacts connected to the end-of-life stage are much lower than the ones at the product stage. Indeed, only the waste processing (Module C3), disposal (Module C4), and the benefits beyond the building life cycle (Module D) are here considered, which are life cycle stages that do not require a large use of energy and materials. The amount of non-hazardous waste disposal is instead much higher than that at the product stage, and it represents the main impact connected to a building's end-of-life.

Considering the GWP indicator, the results are quite similar but vary from solution to solution. For the timber shell, the major benefits are given from the carbonation of foundation concrete in Module C4 and from the reuse/recycle/incineration of materials in Module D. However, these benefits, resulting in negative values of $kgCO_2eq.$, are counterbalanced by the high impacts of the CLT panels in Module C3, which are due to the instantaneous release of the biogenic carbon stored in Module A1 (then recovered in Module D for the reused elements) and the impacts of the incineration process. On the other hand, for the diagrid and wall solutions, negative impacts are present both in Module C4 for the carbonation of the concrete, and in Module D for the reuse/recycle of materials, especially concrete and steel rebars and profiles. The highest benefits are obtained for the RC wall solution due to the presence of higher quantities of concrete and steel rebars. It should be noted that, if each scenario of Section 4.2.1 were considered for the timber shell solution, positive values of $kgCO_2eq.$ would be obtained, reaching a value as high as 8.53×10^4 $kgCO_2eq.$ for the worst-case scenario (Scenario 4, 100% landfill for the CLT panels).

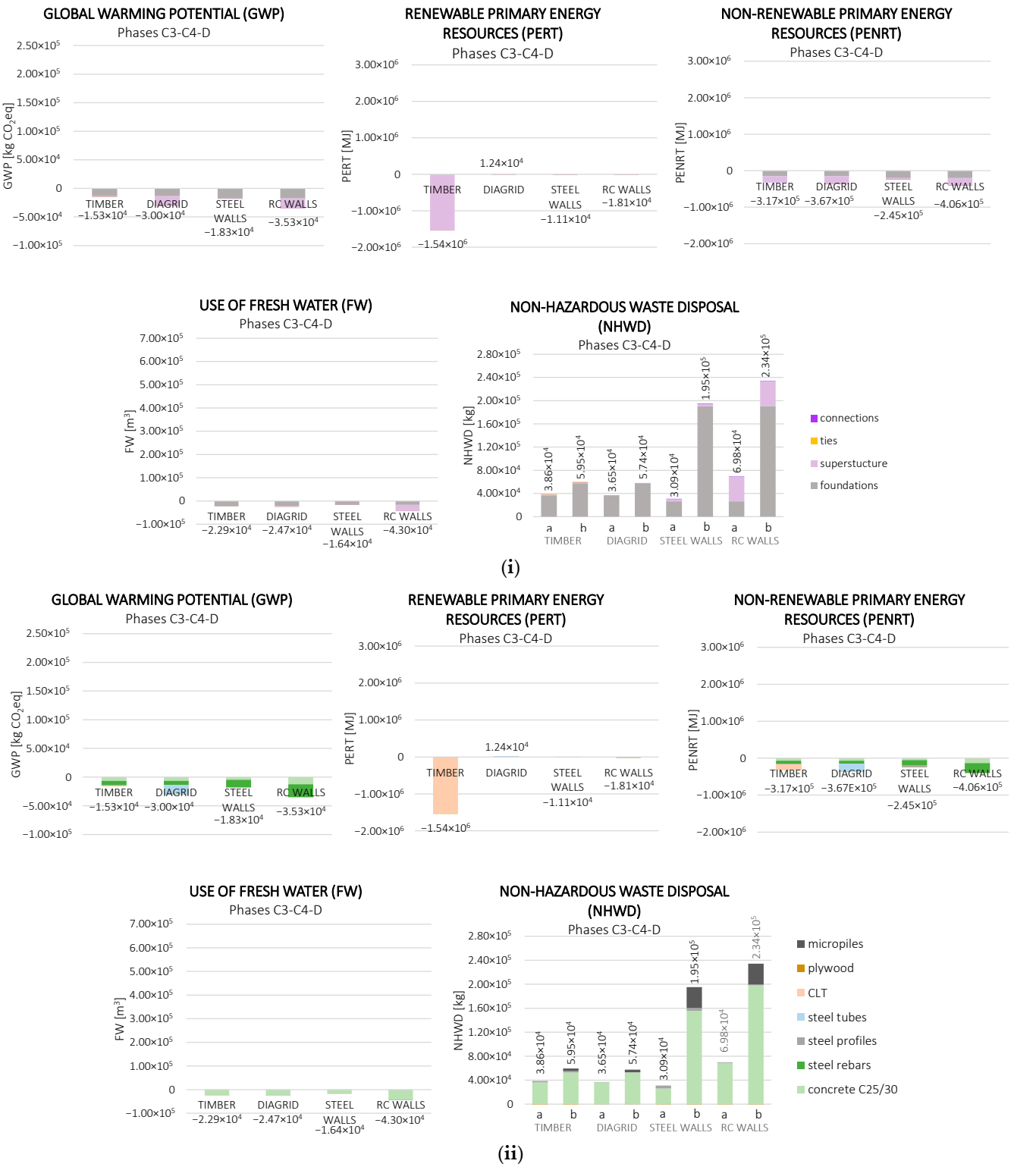

Figure 12. Environmental impacts at the end-of-life stage (Modules C3–C4–D) considering the additional exoskeleton. Data are disaggregated considering the different parts of the structural system (**i**) and the different structural materials (**ii**). (The NHWD indicator both disregards 'a' and considers 'b' micropiles as waste).

Considering the PERT indicator, impacts of diagrid and RC wall solutions may be considered as negligible with reference to the timber shell solution. In the case of the timber panels, great benefits are connected to both the reuse and incineration of the panels.

As for the use of fresh water (FW), the benefits are directly connected to the recycling of concrete elements; however, it should be noted that, using the recycled concrete just for the substitution of virgin aggregate (downcycling process), the amount of saved water is not comparable to the amount of fresh water adopted to produce new concrete elements (Figure 9).

Finally, in regard to the NHWD indicator, the highest impacts are connected to the presence of RC elements in the foundation for the timber and steel retrofit solutions, and in both the foundation and the superstructure for the RC wall retrofit solution. These impacts increase further when the micropiles are considered, where additional concrete and the iron micropiles are also added to the total end-of-life waste (scenario 'b' in the NHWD indicator of Figure 12).

4.4. Total Impacts at the Product and End-of-Life Stages

In this Section, total impacts, calculated by aggregating the previously computed values at the product and end-of-life stages, are discussed, considering: (1) only the exoskeleton composed of foundations, superstructure, connections and ties (Section 4.4.1); and (2) the global system constituted by the exoskeleton and the existing building, whose impacts are then compared to the impacts connected to the structural system of a new equivalent RC building that has the same structural performance of the retrofitted building (Section 4.4.2). The structural systems of the existing and the new buildings were described in Section 3.4.2 and their Bill of Materials is reported in Appendix A.

4.4.1. LCT-Based vs. Traditional Renovation

Considering only the exoskeletons (superstructure + foundations + connections + ties), the results previously analyzed in Sections 4.1–4.3 are herein summed to obtain the total impacts caused by production (Modules A1–A2–A3) + end of life (Modules C3–C4–D) (Figure 13).

For all the considered indicators, shell solutions are always more sustainable than wall solutions. This is mainly due to the impacts of the foundation system and, especially, of the number of micropiles. The material adopted for the exoskeleton is also significant. Especially for the GWP, PERT, and PENRT indicators, and when considering the best scenarios discussed in Section 4.2, the timber shell solution is better than both the steel diagrid solution and, even more so, the steel and RC wall solutions. As for the CLT panels, this is due both to the use of a biomaterial able to store carbon, and to the considered high rate of reuse. Results would be worst if other scenarios of Section 4.2.1 were considered. For the steel diagrid solution, impacts are higher than timber; however, better performance would be achieved if higher rates of reuse of the steel elements of the diagrid superstructures were considered, i.e., if LCT principles such as standardization of the elements and of the connections (dry technologies, bolted instead of welded connections, etc.) were used to improve reusability. The traditional RC wall solution is the least sustainable solution. This is due to the high impacts in the product stage, to the low rate of recyclability and low quality of the recycled material, which may not be reused as virgin material, and to the high amount of water required for concrete production. Finally, the steel wall solution lies in between the shell solutions and RC wall solution. This means that the impact of the RC foundations of the wall solutions jeopardizes the benefits connected to the adoption of LCT principles.

4.4.2. Renovation vs. Demolition and Reconstruction

The data of Section 4.4.1 are herein integrated with the impacts connected to the existing building (EB) in order to consider the complete renovation scenarios. In this case, the existing structure being built in 1970, its service life is already exhausted; thus, the impacts connected to the product stage of the existing building are not considered and only the impacts of the end-of-life stage are accounted for (referred as 'End of Life—EB' in Figure 14). The renovation scenarios are then compared with the demolition and recon-

struction scenario, which considers the preliminary demolition of the existing building and the construction of a new RC structure that has the same structural performance of the retrofitted buildings (Figure 14). Boundaries and scope of the analyses are described in Section 3.4.2 and Figure 8.

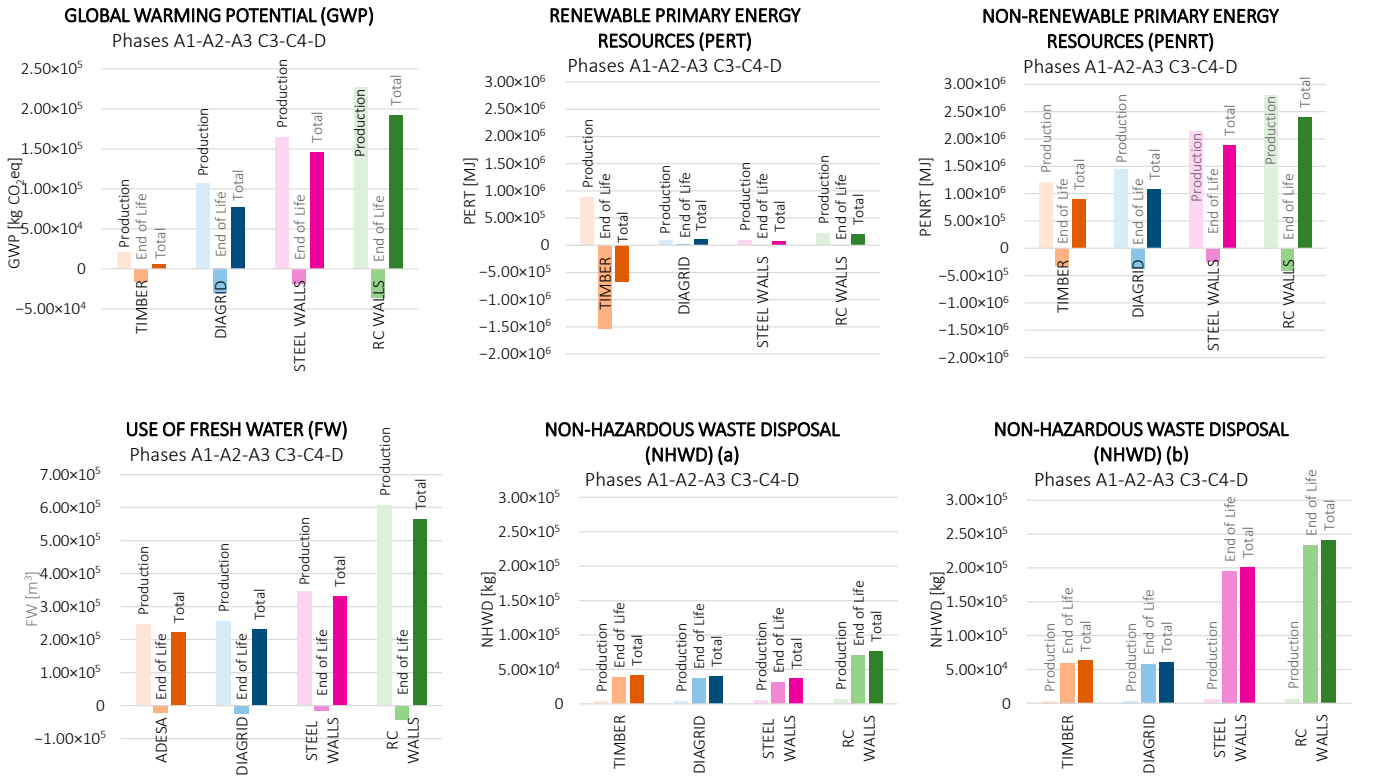

Figure 13. Environmental impacts at the product stage (Modules A1–A3) and end-of-life stage (Modules C3–C4–D) considering the additional exoskeleton. (The NHWD indicator both disregards (a) and considers (b) micropiles as waste).

For each of the considered indicators, the demolition and reconstruction scenario generates much higher impacts than the renovation scenarios, where only the exoskeleton is added to the existing building.

It should be noted that the contribution of the existing building always leads to negative impacts, with the exception of the NHWD indicator. This illusory beneficial effect is strictly connected to the boundary of the system; Modules C3 and C4 do not require a high amount of energy or water, hence, at the End of Life, the avoided impacts considered in Module D dominate the response. If Modules C1 and C2 were also accounted for, higher impacts would have been expected. On the other hand, when considering the NHWD indicator, the waste generated for the demolition of the existing building represents a relevant contribution. For this indicator, if the micropiles in the ground are not considered as waste (case a of Figure 14), the existing building is the major contribution for all the renovation scenarios and a great contribution for the demolition and reconstruction scenario. In this case, the demolition and reconstruction scenario is responsible of an amount of waste that almost doubles the waste of the renovation scenarios. On the other hand, when the micropiles are considered as waste (case b of Figure 14), the total amount of waste of the shell retrofit solutions remains low, while the waste produced by the wall solutions is almost equal to the one of the demolition and reconstruction scenario. The only difference, in this case, is that, in this latter scenario, the waste due to the demolition of the existing building is produced immediately during construction, while in the renovation scenarios all the waste is produced at the End of Life of the retrofitted building.

Figure 14. Environmental impacts at the product stage (Modules A1–A3) and end-of-life stage (Modules C3–C4–D) considering both the renovation scenario (i.e., the structure of the existing building (EB) and exoskeletons) and the demolition and reconstruction scenario (i.e., demolition of the structure of the existing building (EB) and construction of the structure of the new RC building. The NHWD indicator both disregards (a) and considers (b) micropiles as waste. In 'RC WALLS' and in the 'demolition and reconstruction' scenarios, the shaded area represents the contribution of the seismic RC walls).

4.5. Major Findings and Research Needs

Based on the obtained results, some considerations on the process of structural renovation of existing buildings can be drawn. Starting with the building life cycle stages:

- At the product stage, with the sole exception of the waste production (NHWD) indicator, all the indicators are higher than at the end-of-life stage, given that material and energy-intensive activities are expected during the production of the structural systems. In addition, at this stage, the choice of the construction material is critical, and the use of recycled/reused materials and biomaterials should be highly recommended.
- At the End of Life, the greater impacts are associated with waste production, even when one considers high levels of reuse and recycling. The adoption of recyclable/reusable materials and of LCT principles allowing for easy deconstruction guarantee a strong reduction in the impacts, as highlighted in the discussion of the end-of-life scenarios. Nevertheless, high amounts of waste are still generated, especially due to the presence of the RC foundation system. It should be noted that, in this study, the less impactful end-of-life scenarios were considered the timber and steel solutions; however, if lower ratios of reuse/recycling were considered with respect to the ones of Table A3 and Section 4.3, the benefits of Module D would be jeopardized, leading to positive values of the impacts at the End of Life.
- In this research, only the product and end-of-life stages were considered, but impacts due to other life cycle stages may also be worth assessing. Modules A5 and C1 would be needed to evaluate the effectiveness of modularity and prefabrication in the construction and deconstruction phases, and the possible presence of trade-offs caused by the use of dry techniques. Modules B3–B5 would be required to evaluate the advantages of adopting seismic retrofit solutions designed to minimize/lump the damage in the case of earthquakes and other natural disasters. In this case, innovative LCA methods that also include hazard losses should be adopted.

With regard to the consideration of materials and elements in the process of structural renovation of existing buildings:

- The use of concrete as construction material is responsible for significant environmental impacts, especially when considering GWP (despite the beneficial contribution of carbon sequestration), PENRT and FW indicators. Concrete is frequently adopted, even in wooden or steel solutions for foundations and floors. Not surprisingly, the need to develop more sustainable concrete [43] and alternative foundation and flooring systems is nowadays acknowledged as a priority and much research effort is being dedicated to this subject. The adoption of biomaterials is instead fundamental for environmental impact mitigation and should be further improved by adopting fast-growing bio-based materials [25].
- In regard to the building elements, the analyses highlight the relevance of the impacts of the foundations both at the product and end-of-life stages, as well as the need to reduce them for the sake of sustainability. This study shows that one strategy may be the reduction of the number of micropiles, e.g., by adopting shell solutions rather than wall solutions. In addition, since the principal impact of foundations comes from to the use of concrete, as previously noted, more sustainable concrete mixes or different materials should be considered for foundations, such as steel beams and reusable piles, as also suggested in [30].

5. Conclusions

The global urgency to reach carbon neutrality by 2050, associated with an awareness of the significant environmental impacts of the construction sector, has underlined the need to foster sustainability, circularity and resilience of the built environment. In order to reach the zero-carbon goal in the construction sector, a great paradigm shift is thus required, moving from a linear to a circular economy, and embracing a Life Cycle Thinking (LCT) approach. This challenge should engage all the stakeholders of the value chain, from manufacturer to end users, attributing a pivotal role to designers and structural engineers, whose actions may be critical in strongly reducing the embodied carbon of the built environment by adopting better design choices.

In this paper, an overview of design performance objectives and principles inspired by Life Cycle Thinking, enabling the transition towards a more sustainable construction sectors, is provided. Among the performance objectives, design for eco-efficiency, reparability, durability and maintenance, adaptability and flexibility, deconstruction, reuse and recycling should be pursued. Unlike the current state of the art, this research aims to promote the pursuit of all these objectives together, enhancing the concept of Life Cycle Structural Engineering (LCSE), with the aim of optimizing efforts to reduce the impacts of construction and avoiding the shifting of impacts from one life cycle building stage to another (which would, on the whole, be of no benefit). To this aim, LCT principles to be implemented from the early design stages are summarized and presented considering three different levels: material, construction technique and planning levels (Figure 4).

To validate the effectiveness of the adoption of an LCT approach for the design of sustainable buildings in mitigating the impacts of the construction sector, the proposed design objectives and principles were applied with reference to a case study: the renovation of an existing RC building, typical of the post-WWII building stock. Four alternative iso-performance structural retrofit solutions, either LCT-based or traditional, were designed and comparatively assessed, and later compared with a demolition and reconstruction scenario. The criticalities of relevance, in terms of building life cycle stages, building materials and components, were discussed, and possible mitigation strategies and research needs were proposed. The aim of the study was to show that solutions designed according to an LCT approach lead to impacts along the building life cycle that are considerably lower with respect to the impacts of traditional solutions.

The considered retrofit solutions were CLT panel and steel diagrid shell exoskeletons, and steel and RC wall exoskeletons. The timber and steel solutions were designed according to the proposed LCT principles, while the RC wall solution was conceived as a traditional wall retrofit intervention. All the solutions were conceived as structural exoskeletons, assembled outside the building to minimize interference with the building usage, and the same energy upgrading measures were assumed. The estimation of the impacts was made on the basis of the structural layer of the building, through simplified Life Cycle Assessment (LCA) analyses based on available Environmental Product Declarations (EPDs). The product and end-of-life stages were considered in the analysis (Modules A1–A3 and C3–C4–D, according to [16]), and five environmental indicators were considered: Global Warming Potential (GWP), Renewable (PERT) and Non-renewable (PENRT) primary energy resources, use of fresh water (FW) and Non-hazardous waste disposal (NHWD).

Analyzing the results of the considered case study, it may be concluded that, when comparing alternative retrofit interventions, solutions designed according to LCT principles allow a great reduction in impacts with respect to the traditional cast-in-place RC solution. In addition, the adoption of shell solutions should be preferred to walls solutions because of the reduction in the foundations' impacts. In order to further improve the environmental performance, recyclable/reusable foundation systems should be considered, possibly avoiding RC as a material or adopting more sustainable concretes [43]. In addition, strategies allowing for higher rates of reuse for steel elements (and to guarantee the considered high rate of reuse of the timber elements) should be studied.

With regard to the comparison between the renovation and the demolition and reconstruction strategies, it may be stated that renovation should be preferred, unless demolition is mandatory, due to the significant impacts connected to the latter scenario. It should be noted that, in this study, a traditional RC building was considered as a new construction, but new LCT-based construction technologies may be developed to reduce the impacts of new buildings too.

Further developments of this research envision the estimation of the impacts in the other life cycle stages by means of LCA methods that also include loss assessment. Further research on the possible application of the proposed LCT principles to define new LCT-based retrofit techniques and operative design frameworks and tools is also required, with the aim of rendering the concept of LCSE increasingly more common in the design practice.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Bill of materials (BOM) of the designed exoskeletons.

Element Category	Material	Unit	Timber Shell	Steel Diagrid	Steel Walls	RC Walls
Foundations	Concrete C25/30	m^3	67.29	67.29	95.31	95.31
	Formwork	m^3	1.33	1.33	0.98	0.98
	Reinforcement steel	ton	6.28	6.28	11.35	11.35
	Steel profiles	ton	0.89	0.89	1.77	1.77
	Micropiles	m	210.00	210.00	1650.00	1650.00
Superstructure	CLT	m^3	95.76	-	-	-
	Steel tubes	ton	-	27.02	-	-
	Steel profiles	ton	-	-	22.81	-
	Concrete C25/30	m^3	-	-	-	70.88
	Formwork	m^3	-	-	-	5.17
	Reinforcement steel	ton	-	-	-	8.35
Ties	Steel profiles	ton	8.86	1.24	1.24	1.24
Connections	Steel profiles (studs)	ton	0.57	0.57	0.70	0.70
	Steel profiles (stringcourse)	ton	4.51	0	4.51	4.51

Table A2. Bill of materials (BOM) of the structure of the existing building and of the new RC building.

Element Category	Material	Unit	Existing Building	New RC Building
Foundations	Concrete C25/30	m^3	78.23	197.55
	Formwork	m^3	5.80	5.80
	Reinforcement steel	ton	1.18	11.71
Frame (beams, columns, stairs, staircase walls)	Concrete C25/30	m^3	104.89	150.12
	Formwork	m^3	10.07	11.35
	Reinforcement steel	ton	7.41	14.62
Floors/Roof	Concrete C25/30	m^3	83.91	100.85
	Formwork	m^3	17.60	17.60
	Reinforcement steel	ton	3.01	3.01
	Welded mesh	ton	-	4.22
	Floor hollow clay blocks	ton	75.86	98.07
	Clay tiles	ton	13.06	13.06
Infills	Hollow clay bricks	ton	67.83	67.83
	Mortar	ton	10'450.02	10'450.02

Appendix B

Table A3. List of the adopted EPD and considered end-of-life assumptions for each material of the BOM.

Material	EPD Owner	Country	Validity (Year)	Modules	End-of-Life Assumptions
Concrete C25/30	Unical	IT	2022	A1–A3	-
	Beton	FR	2024	C3–C4–D	75% recycling, 25% landfill (C3: Treatment of valuable demolition waste: crushing to obtain gravel for road use and storage; Carbonation of concrete waste—75% of the product landfilled carbonate) (D: substituting virgin material—natural gravel for road applications)
Formwork	Panguaneta	SE	2025	A1–A3 + C3–C4–D	49% material recovery, 4% energy recovery, 13% incineration, 34% landfill
Reinforcement steel	Alfa Acciai	IT	2025	A1–A3 + C3–C4–D	Content of recycled materials $\geq$ 97% (D: net value between direct impact, i.e., recycling steel in Electric Arc Furnace, and avoided impact, i.e., producing steel from iron ore in Basic Oxygen Furnace)
CLT	Stora Enso	FI	2026	A1–A3 + C3–C4–D	Four alternative scenarios: 1. Reuse: 100% CLT is reused in coherent form (D: substituting virgin material—product) 2. Recycling: 100% CLT chipping for recycling (D: substituting virgin material—wood chips) 3. Incineration: 100% CLT incineration for energy recovery (75% efficiency) (D: substitution of natural gas in heat production) 4. Landfilling: 100% CLT is landfilled (D: the methane uptake from landfill partly substitutes natural gas in heat production)
Steel tubes	Profiltubi	IT	2026	A1–A3	-
	1—Del Acero	ES	2025	C3–C4–D	95% steel recycling (D: production of steel is avoided)
	2—ArcelorMittal	LU	2025	C3–D	11% reuse, 88% recycling, 1% landfill (C3: sorting and shredding of after-use steel that is recycled and non-recovered scrap due to sorting efficiency which is landfilled—conservative value of 1%) (D: avoided manufacturing of structural hollow sections)
Steel profiles	Beltrame	IT	2024	A1–A3	-
	ArcelorMittal	LU	2024	C3–C4–D	11% reuse, 88% recycling, 1% landfill (C3: sorting and shredding of after-use steel that is recycled and non-recovered scrap due to sorting efficiency which is landfilled—conservative value of 1%) (D: avoided manufacturing of structural steel sections and merchant bars)

Table A3. *Cont.*

Material	EPD Owner	Country	Validity (Year)	Modules	End-of-Life Assumptions
Micropiles	Tiroler	AT	2022	A1–A3 + C3–C4–D	In principle, it is possible to recycle ductile iron piles. However, usually, this is not done for economic reasons and the piles remain in the ground
Welded mesh	Alfa Acciai	IT	2025	A1–A3 + C3–C4–D	Content of recycled materials ≥ 97% (D: net value between direct impact, i.e., recycling steel in Electric Arc Furnace, and avoided impact, i.e., producing steel from iron ore in Basic Oxygen Furnace)
Floor clay blocks & Clay blocks	Wienerberger	IT	2025	A1–A3 + C3–C4–D	95% recycling, 5% landfill (D: avoided virgin material—the mixed aggregate, consisting of brick and its complements, if necessary, cleaned, crushed and screened may be reused as a secondary material in completion works, subgrade, or as aggregate)
Clay tiles	San Marco	IT	2024	A1–A3 + C3–C4–D	70% reuse, 30% landfill (D: avoided virgin material—clay tiles)
Mortar	Mapei	IT	2022	A1–A3 + D	(D: Credits from incineration of packaging)

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