A Multi-Step Design Framework Based on Life Cycle Thinking for the Holistic Renovation of the Existing Buildings Stock

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Abstract. In recent years, the transition to a sustainable society has highlighted the importance of tackling a holistic renovation of the existing building stock, able to contextually solve its structural, energy, and architectural deficiencies. Nevertheless, in practice, the cost of the intervention, the building downtime, and the potential relocation of the inhabitants have been recognized as major barriers to the renovation. To overcome such barriers and foster sustainability, eco-efficiency, and resilience, new design approaches and solutions sets have been proposed. However, given the lack of a global vision of current regulations, a design framework able to conjugate technical and functional performances with principles of sustainability and feasibility is still required. In this paper, a new multi-step design framework is proposed, which, for the first time: 1) adapt the three pillars of sustainability to the renovation of the existing buildings interpreting them as reduction of environmental impacts, increase of safety and resilience, and overcoming of the major barriers to the renovation; 2) introduce a new Life Cycle perspective that also considers impacts and loss associated to structural decay and vulnerability of existing buildings; 3) shift from an ex-post perspective to an ex-ante framework, to be used since the initial design steps.

1. Introduction and research motivation

European existing building stock may be considered unsustainable from many points of view: energy consumptions, CO_2 emissions, raw material depletion, etc. However, it should be acknowledged that also **structural decay and obsolescence** contribute to increase the impacts of existing buildings in any aspect of sustainability [1]. From an environmental and economic point of view, it should be considered that a building may experience damage and collapse due to both ordinary static loads and under extraordinary loads, such as earthquakes/flash floods/tornadoes/etc. Debris disposal, material consumption, and CO_2 emissions related to demolition, repair and reconstruction actions generate indeed significant impacts throughout the building life cycle [2]. From a social point of view, in addition to potential casualties, the need to relocate the building functions during these actions represents a great trouble to the building owners and inhabitants.

In order to ensure a sustainable renovation process as to reach the targets of the *European Roadmaps 2020* and *2050*, all building deficiencies, including structural safety and resilience, should thus be addressed. Nevertheless, the current approach to the renovation is still very sectorial. Today, three main approaches may be followed: i) demolition and reconstruction; ii) sole energy upgrade;

iii) sole structural upgrade. In the first case, a great amount of waste is generated and new materials need to be produced for the construction of a new building; furthermore, inhabitants should be relocated, thus creating huge economic, environmental, and social impacts. In the cases ii) and iii), the renovation process would lead to a retrofitted building which is either unsafe or energy consuming, respectively (figure 1). It should also be considered that, although many techniques have been studied for the renovation of existing buildings under a sustainable perspective (either energy, structural, or combined), the renovation rate is still very low (about 1%) due to the high cost and duration of the retrofit intervention and to the need to relocate the building's activities during the works [4]. Recent studies have highlighted the need to embrace a new **holistic approach to the renovation**, with the final aim of improving the retrofitted building performances according to sustainability principles [3].

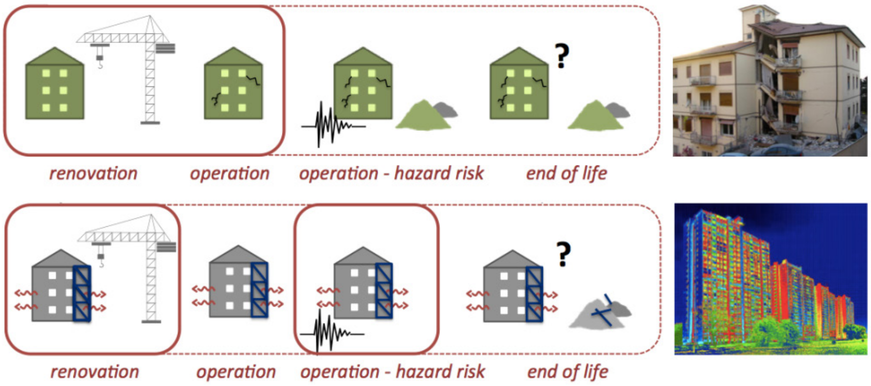

Figure 1. The results of an uncoupled approach to the renovation of the existing building stock: when sole energy refurbishment is carried out, buildings remain structurally vulnerable (top); when a sole structural intervention is applied, they still have high energy consumption and GHG emissions (bottom). In both cases, they may not be considered as sustainable.

Following these considerations, a next-generation design framework is proposed in this paper. The new framework should:

1. redefine design objectives and targets also considering possible interferences/interactions among energy/architectural/structural retrofit interventions;
2. include sustainable principles inspired by a **Life Cycle Perspective** [5], also considering hazard risk, thus shifting from a static to a stochastic perspective for the design and the evaluation of the impacts;
3. estimate the most sustainable solutions from the beginning of the design phase, thus reducing the effort of designing too many alternative solutions.

2. The Life Cycle perspective in building renovation

The need to pursue the sustainability of the existing building stock requires the adoption of a completely new approach to the renovation, which is aimed at reducing the overall impacts throughout the building life cycle from the stage of the retrofit intervention to its end of life. Under this new perspective, the intervention should be designed not just to fulfil the code/guidelines requirements at the time of the design but should also consider all the potential events that the retrofitted building may experience until its end of life. Differently from the current Life Cycle methods, the implementation of this new approach allows the consideration of possible extreme events (e.g. earthquakes, flood, etc. depending on the hazard of the site), change in destination use, changes in the code requirements, etc. since the first step of the design.

If the sustainability of retrofit interventions is analysed from this new perspective, the results can be completely different from what expected. As an example, when the carbon footprint and economic impacts of a building are calculated looking at only the energy consumption of a building, i.e. without taking into account losses and GHG emissions due to possible earthquakes for buildings in seismic prone areas, the results underestimate the impacts. In this regard, Belleri and Marini [6] showed that, using a LCA approach, buildings located in highly seismic prone areas may double their annual operational carbon footprint after thermal refurbishment. Similarly, structural interventions may result unsustainable when they require the relocation of the inhabitants, when the demolition of the building finishing is necessary, when the building is neither reparable nor adaptable to structural/functional changes, or when the interventions prevent disassembling with a selective dismantling process at the building's end of life (figure 2) [5].

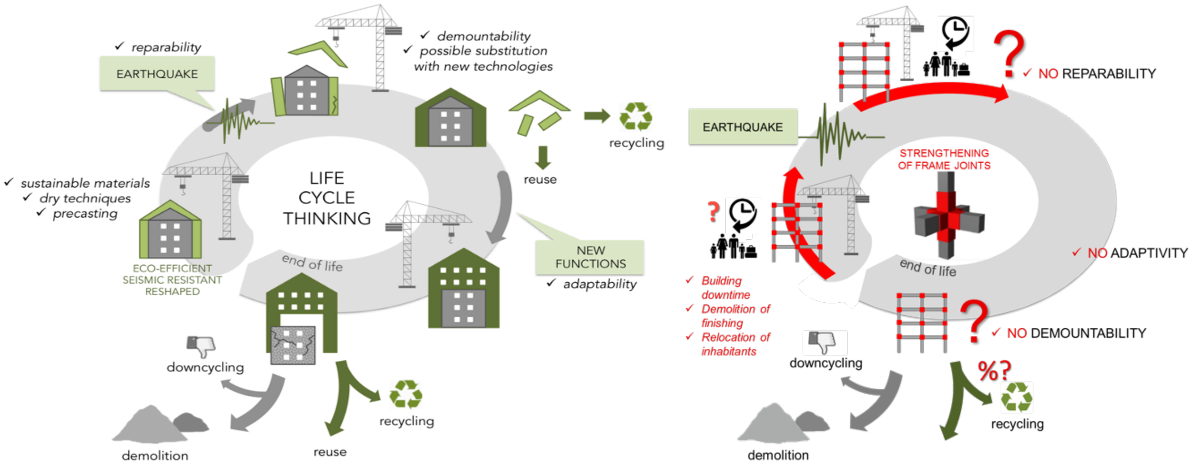

Figure 2. When applied to building renovation, Life Cycle Thinking (LCT) should consider the environmental, economic, and social impacts that may be generated by all the events that the retrofitted building may experience until its end of life (left). Under this new perspective, traditional retrofit actions may result extremely unsustainable (right). (adapted from [3] and [5])

On the contrary, when a new design framework based on Life Cycle Thinking (LCT) is considered for the renovation of existing buildings, new principles can be defined ensuring the sustainability of the intervention itself. At each phase of the building life cycle, several sustainability needs can be identified, which may belong to the environmental, social, or economic fields (figure 3). For instance, in the initial decision-making stage, costs and duration of the retrofit works should be reduced, avoiding, at the same time, inhabitants' relocation.

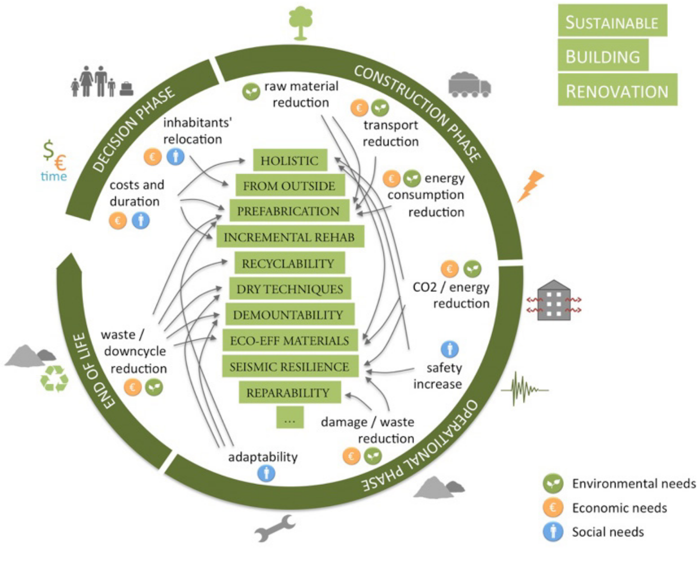

Figure 3. When designing sustainable building renovation interventions, all the environmental, economic, and social needs of the building from the retrofit design to its end of life should be evaluated, and new sustainable LCT principles should be considered both for the concept and the design of the solution.

During the implementation of retrofit interventions, impacts connected to raw material depletion, transport, and energy consumption should be reduced; during the operational stage, GHG emissions, energy consumption, and waste production should be limited, structural safety increased, possible damage induced by hazard risks reduced, and adaptability pursuit; finally, at the end of life of the building, the amount of waste generated by the dismantling and the demolition should be reduced as well. In order to fulfil those needs, new principles should be introduced within sustainable design frameworks. The adoption of a holistic renovation applied from outside of the building [3], the concept of incremental rehabilitation [7] (which divides the overall intervention into multiple steps, each one aimed at increasing the safety of the building), the use of prefabricated, demountable, dry techniques, the use of eco-efficient and recyclable materials are some of the new principles that should be followed when considering a Life Cycle perspective for a sustainable building renovation.

3. Existing framework for a sustainable renovation: a critical review

Recently, the need for a sustainable renovation of the existing building stock has oriented the research community towards the study of new design methodologies able to fulfil simultaneously environmental, economic, and social sustainability. Different methods have been proposed so far, encompassing some, but not all the above-mentioned aspects. Mainly, these researches are aimed at integrating environmental and social sustainability – intended as reduction of CO_2 emissions and increase of the health and indoor comfort, economic sustainability, and safety against the seismic loads, which may also be considered as a reduction of the economic, social and environmental impacts along the building's life cycle.

In order to promote the implementation of green retrofitting of existing buildings, various researches have first focused on the cost-effectiveness of retrofit actions, including new economical decision-making models. An overview of these methods, along with the analysis of the main barriers and challenges to green retrofitting, may be found in Jagarajan et al. [8]. Considering economy and safety (Social aspects), Calvi [9] compared alternative seismic retrofit options based on the ratio between the difference of the building Expected Annual Loss (EAL) before and after the retrofit and the cost of the intervention itself, while Vitiello et al. [10] proposed an enhanced LCC method, which integrates expected direct and indirect seismic losses over the building lifetime. Coupling environmental needs and safety, Comber et al. [11], Menna et al. [12], Wei et al. [13], and Belleri and Marini [6] quantified the seismic risk role on the environmental impact assessment of existing buildings.

Only very few researches have recently tried to couple all the three aspects of sustainable renovation. Mauro et al. [14] proposed a sustainability assessment framework, where the cost-optimal energy retrofit solution, obtained with a genetic algorithm procedure, is identified, and the impact of the expected economic losses due to seismic damage is assessed throughout the building lifecycle. The solution, however, still do not identify the most cost-effective structural retrofit solution. Lamperti Tornaghi et al. [15] and Wei et al. [16] proposed solutions where Life Cycle Assessment (LCA) and seismic expected annual losses (EAL) are combined following a Life Cycle Cost (LCC) perspective. The best retrofit option was evaluated by expressing losses and environmental impacts as costs.

It should be noted that: a) all the aforementioned approaches are "ex-post" evaluations, where retrofit strategies are evaluated at the end of the design process; b) the approaches do not guide the selection of sustainable interventions following LC principles, but often are limited to evaluating the CO_2 emissions of the technical solution "from cradle to gate" – i.e. before arriving to the construction site; c) the design of the intervention do not correct the pre-defined targets to take into account interferences and to reduce potential impacts during the life cycle; d) these approaches do not adopt real synergic tools, but carry out separated analyses and considerations adopting sectorial tools; e) the best retrofit option is obtained by expressing performances of very different nature, such as economic losses and environmental impacts, just in terms of costs, which cannot be determined with a straightforward method, and thus resulting in an oversimplification of the problem [17]. Mainly, these approaches have been specifically developed for the assessment of end-retrofit solutions that were designed separately according to available sectorial methods, neglecting the possibility to adapt current design practices to the multifaceted initial building needs and to the life cycle performances. A framework for the holistic design of retrofit solutions fostering safety, resilience, well-being, and sustainability, with these principles included in each step of the design process in a Life Cycle perspective, is not yet available.

4. A sustainable multi-step design framework based on Life Cycle Thinking

A new holistic framework for the design of retrofit interventions is here proposed. The framework is aimed at introducing the principle of Life Cycle Thinking in the design process, leading to the selection and the design of the most sustainable option.

The proposed design framework envisions a 4-step procedure (figure 4):

- Step 1 considers the comprehensive building audit in its as-is situation, evaluating the deficiencies/needs and dynamics in all relevant areas of intervention: safety, energy, operational, environment etc. This allows defining and addressing the minimum performance objectives in the renovation process. Any possible constraint should also be considered, especially the ones connected to the overcoming of renovation barriers (e.g. inability of relocating the inhabitants during structural retrofit, possibility of incremental rehabilitation, etc.). In this step, the evaluation of the building residual life is assessed since most of the buildings requiring renovation have exhausted, or nearly exhausted, their design structural life and the first major decision is between renovation and demolition [18].
- In Step 2, the most sustainable solutions are derived considering the building and its occupants' needs, the life cycle perspective, and the constraints identified in the previous step. Weights are assigned using an evaluation form that establishes sustainability criteria in each area. Such weights are derived using a one-level hierarchy [19] based on qualitative priorities addressed by owners/investors/developers, by minimum performance objectives and by national or international policies. If no solution fully addresses the building needs, this step fosters the research of new solutions.
- In Step 3, selected interventions are designed according to a multi-performance energy and structural Performance Based Design (PBD). Typical target values may be specifically corrected based on LCT criteria and on interactions/interferences arising from different retrofit options.
- In Step 4, a comparative quantitative assessment of the different alternative solutions performances in terms of environmental regeneration, human safety, energy efficiency, and costs throughout the building life cycles is carried out adopting Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) procedures. In this phase, the influence of natural hazards, such as seismic hazard, should be included by specifically determining the expected annual loss (EAL) in terms of overall costs (related to structural damage, life cycle phases, energy consumptions etc.) and environmental footprint. The return period of the investment both in monetary, expressed via metrics like breakeven time, and environmental terms is also evaluated. The best solution is detected by ranking them following Multi-Criteria Decision Making (MCDM) approaches (e.g. [20] and [21] among others). Similarly to Step 2, specific weights need to be assigned.

The framework is developed to be the interface among different stakeholders, setting shared objectives for the existing building renovation to be addressed by all the players in the construction chain. It can be adopted by design professionals starting from the conceptual design of sustainable solutions; by owners and investors as a decision-making tool; and by policy makers, local administrative agencies and urban planning specialists, as a guideline to promote sustainable urban regeneration.

In an early version of the framework, it may include existing design and assessment tools, so as to be easily used by the professionals. However, some drawbacks of the existing tools are put in light when considering them under a Life Cycle perspective. PBD procedures should be expanded. Performance objectives must be reviewed under the new principles of life cycle thinking, and targets must be updated as to consider interferences and interactions between architectural/structural/

functional retrofit interventions. LCA and LCC methods should be updated to pass from static to stochastic by including hazard risks into the process. The structure of the framework is thus kept open as to integrate possible upgraded tools.

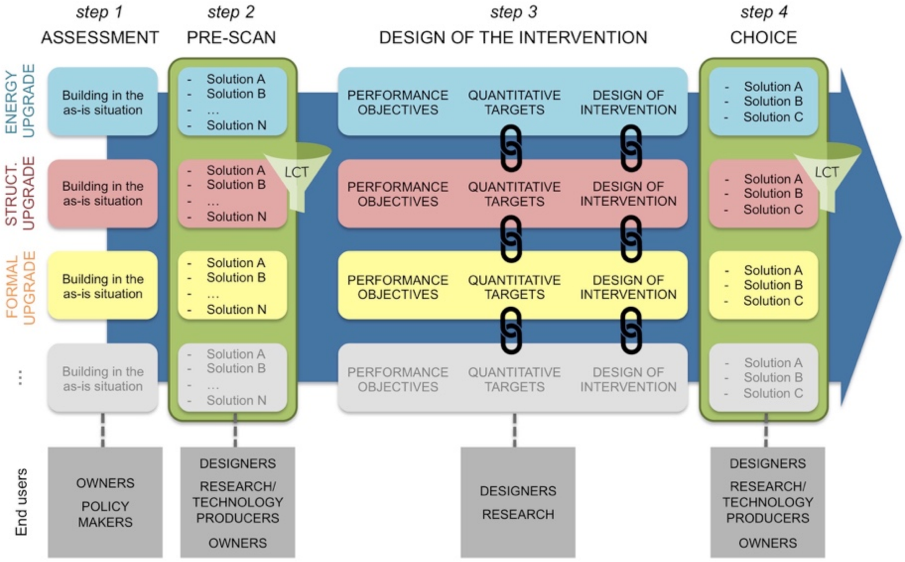

Figure 4. 4-step design framework based on Life Cycle Thinking: phases and end users

5. Novelty of the proposed approach and concluding remarks

In this paper, a 4-step design framework based on the principles of Life Cycle Thinking for the holistic renovation of the existing building stock has been proposed. The proposed approach is innovative with respect of the present state of the art under many point of view:

4. The three pillars of the sustainability are reinterpreted and adapted to the holistic renovation of the existing building stock. Sustainability of the renovation is not just intended as the reduction of GHG emissions and energy consumption, but also as the reduction of the costs of the interventions and of the disturbance to the inhabitants during works (to boost the building renovation rate) and as the increase of the structural safety of the building. This new interpretation of sustainable renovation leads to the definition of new needs for the design of retrofit interventions. New holistic techniques from outside should be studied and interferences and interactions among different solution should be evaluated both in the concept of the retrofit strategy and during the selection of the retrofit design targets. Existing PBD methods should be updated under this new multi-performance and multi-disciplinary approach.
5. A new Life Cycle (LC) perspective is introduced in the procedure for the renovation of the building stock. To be sustainable, the impacts of the building in each phase of its life cycle should be evaluated and minimized. Current Life Cycle procedures do not take into account all the possible actions that can occur to the retrofitted building, especially do not consider the losses associated to possible hazard risks. Under this new perspective, existing LC tools should thus be updated and transformed from static to stochastic.
6. The proposed approach leads to a shift from an ex-post perspective, usually adopted in the traditional "Building Sustainability Assessment" methods, to an ex-ante framework. A pre-screening phase is indeed included before the design phase to select the most sustainable retrofit options on the basis of qualitative LC criteria decided and weighted by owners and investors (e.g. possibility to act from the outside of the building, possibility to apply an incremental rehabilitation, etc.) (figure 5). This way, the design of the solution and the more sophisticated assessment analyses are carried out only for the most suitable options at the last step of the design.

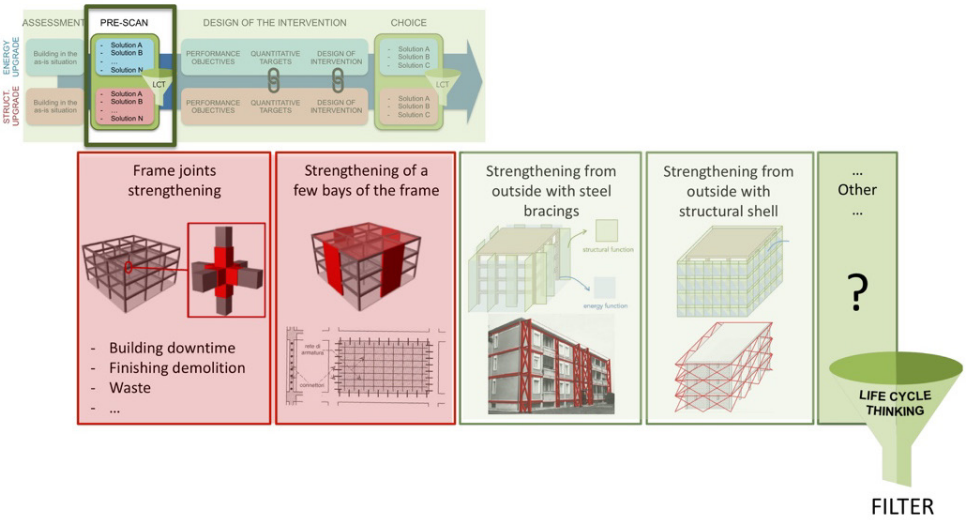

Figure 5. Preliminary assessment of possible structural retrofit solutions under a sustainable point of view adopting qualitative LCT criteria and Multi Criteria Decision Making (MCDM) procedures. This step, preliminary to the design of the solutions, is fundamental to optimize the design process, avoiding the design of unfit solutions and shifting from ex-post to ex-ante sustainable evaluations.

Future developments of this research entail the collaboration among researchers and professional from each discipline in order to develop updated design and assessment tools under this new holistic and LC perspective, the definition of multi-criteria decision-making methods considering new sustainable principles for the pre-screening and final assessment of different retrofit options, and the validation of the framework with reference to case study buildings with different initial conditions and needs.

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