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Life cycle perspective in RC building integrated renovation

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Abstract

Enormous resources are invested in Europe for the transition into a sustainable, low carbon, and resilient society. In the construction sector, these concepts are slowly being applied to the renovation of the existing building stock by enforcing their deep and holistic renovation targeting sustainability, safety and resilience.
Effectiveness of such an approach to the renovation with respect to traditional retrofit actions emerges when broadening the time frame of the analyses, shifting from the construction time to a life cycle perspective. In this case, the potential of the holistic approach becomes clear in reducing costs, impacts on the inhabitants and impacts on the environment over the building life cycle. Within such a new perspective, new technology options are needed to innovatively combine structural retrofit, architectural restyling and energy efficiency measures. Furthermore, a new design approach conjugating the principles of sustainability, safety and resilience over the building life cycle is required. In such a transition, synergistic and cooperative work of researchers, design professionals, and all the stakeholders in the construction sector is required.
In this paper, the basic features of an expanded Life Cycle Thinking (eLCT) approach will be presented, which not only entails the use of recyclable/reusable materials, but also encourages interventions carried out from the outside the buildings to reduce building downtime and avoid inhabitant relocation. In addition, such an expanded LCT fosters the adoption of reparable, easy maintainable, adaptable and fully demountable solutions, such as those featuring dry, demountable and pre-fabricated components. Finally, it addresses the need to account for the End of Life scenario from the initial design stages to guarantee selective dismantling and reuse or recycle to reduce construction waste. Finally, a discussion on the main barriers and challenges in the transition towards this new approach to the renovation of existing building stock is briefly presented.

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Keywords: Life Cycle thinking, Deep renovation, Integrated retrofit, Resilience, Sustainability

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1. Introduction

The urgent need to foster **sustainability** in our society has led to the definition of international policies to be applied in any economic sector. In Europe, Roadmap 2050 envisions a society where greenhouse gas (GHG) emissions are cut by 80-95% with respect to the 1990 levels, but maintaining the actual levels of wellbeing and prosperity (COM 2011). To comply with such a demanding Roadmap, the construction sector should undertake some major corrective actions to reduce its dramatic impacts on the environment, corresponding to 36% of CO_2 emissions, 40% of energy consumption, and 50% of raw material depletion (Marini et al. 2014).

So far, new solutions sets aimed at reducing the environmental footprint of new and existing buildings are under development, but often disregarding some major aspects. Indeed, when applying the concept of sustainability in the construction sector, two main issues must be addressed: the construction rate of new buildings and the multiple deficiencies of the existing ones. Regarding the former, the actual construction rate is very low (about 1% according to La Greca and Margani, 2018), therefore the sole construction of new high performance buildings won't enable meeting the ambitious European targets. Sustainability can only be pursuit by substantially renovating the existing building stock, which is obsolete, heavily energy consuming, and vulnerable to natural and man-induced hazards.

The renovation of the existing building stock can be pursuit both by systematic demolition and reconstruction or by deep retrofit actions. Since demolition and reconstruction is a source of additional environmental impacts due to debris production and disposal, this strategy should only be applied when mandatory (Preservation Green Lab 2012), for example when the exhausted service life of the building cannot be further extended, or when the structural decay is so severe and the quality of the materials is so low as to compromise the safety level for the future years (Casprini et al. 2018). In all the other cases, renovation should be preferred. The renovation measures should effectively extend the building service life and guarantee the maximum level of sustainability over the extended life cycle.

In the last 30 years, the concept of sustainability has acquired great importance, as the growing concern for the environmental conditions of the planet has promoted a new model of sustainable development able to "meet the need of the present generations without compromising the ability of the future generations to meet their own needs" (WCED 1987). When applied to the built environment, the concept of sustainability has been interpreted as the sole reduction of GHG emissions in the operation phase, obtained through reduction of the energy consumption. However, for the renovation action to be effective, the sustainability objective should be broadened and would require the reduction of environmental, economic and social impacts in all the phases of the building life, from the construction to its end of life. Sustainability should also account for the hazard risks reduction, considering that the building may be exposed to extreme conditions, resulting in additional impacts connected to possible damage, or even collapse of the building.

Such a new approach entails a substantial shift in the design perspective: from a design satisfying sectorial building code requirements at the construction time, to a design considering the whole building performances under a Life Cycle (LC) perspective, aimed at reducing costs, impacts on the environment and on the building users, while maximizing comfort and safety. To operate this transition, major barriers must be overcome, leading to the definition of new research needs in many disciplines. An overview of this new LC perspective and a discussion of the main challenges that need to be reckon with are presented in this paper.

2. Life Cycle perspective applied to building renovation

Different approaches may be adopted when conceiving and designing a building. In the past, buildings were designed to meet safety levels for the sole construction phase, disregarding some crucial performances in the operational phase (energy consumption and earthquake resistance, among others) and never considering the end of life scenario (Figure 1.a). The result of such an approach is an energy consuming building stock, responsible of a large share of the total CO_2 emissions, and often vulnerable to man-induced and natural hazards, such as earthquakes. To date, available building renovation strategies can be basically divided into 3 main categories: (i) demolition/reconstruction, which implies additional environmental and social impacts; (ii) uncoupled or partly coupled interventions, in which critical needs associated with structural safety, resilience, energy efficiency, indoor comfort and architectural refurbishment are addressed separately; and only recently (iii) holistic renovation, considering the complex multifaceted needs of an existing building. Regardless the addressed solution, the design is never carried out under a LC perspective.

As for the uncoupled interventions, solely-energy or solely-structural renovation are usually carried out. Energy interventions partly address the building life cycle by focusing on the construction and operation phases. Sustainability is here intended as the selection of eco-efficient construction materials and the reduction of energy consumption in the operation phase (Figure 1.b1). In the renovation, adoption of eco-efficient materials is often operated based on Life Cycle Assessment (LCA) of the construction products from cradle to gate, i.e. connected with the production and transportation to the site and disregarding the end of life scenario. Concerning the operation phase, when a building is upgraded considering its sole energy deficiencies, it may remain vulnerable to hazards, which could induce damage and collapse, therefore additional impacts, besides being a threat for human lives (Pan et al. 2014). In the case of building collapse, such impacts are even higher than those of the un-retrofitted building, because of the additional impacts associated with the components of the energy upgrade systems. It is worth noting that, even nearly-Zero Energy Buildings, obtained through sophisticated energy efficiency measures, not only miss in extending the structural service life of the building, but may be unsafe with respect to even low-intensity earthquakes and may require high structural maintenance costs in order to extend their building life, thus resulting both unsustainable and non-resilient solutions.

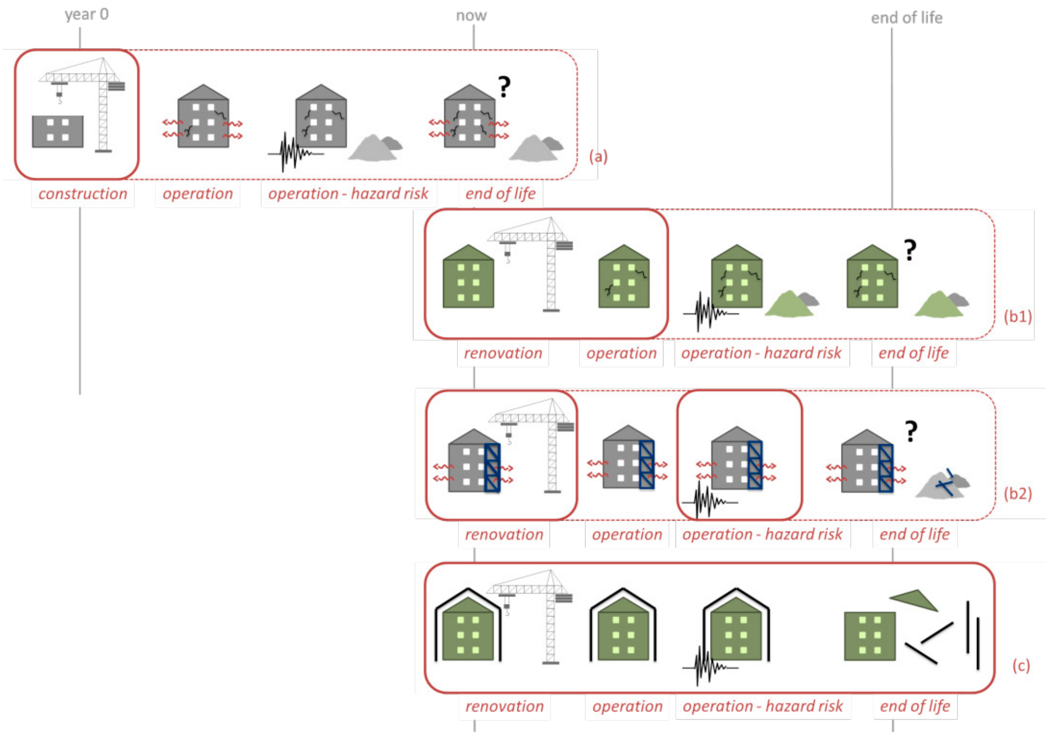
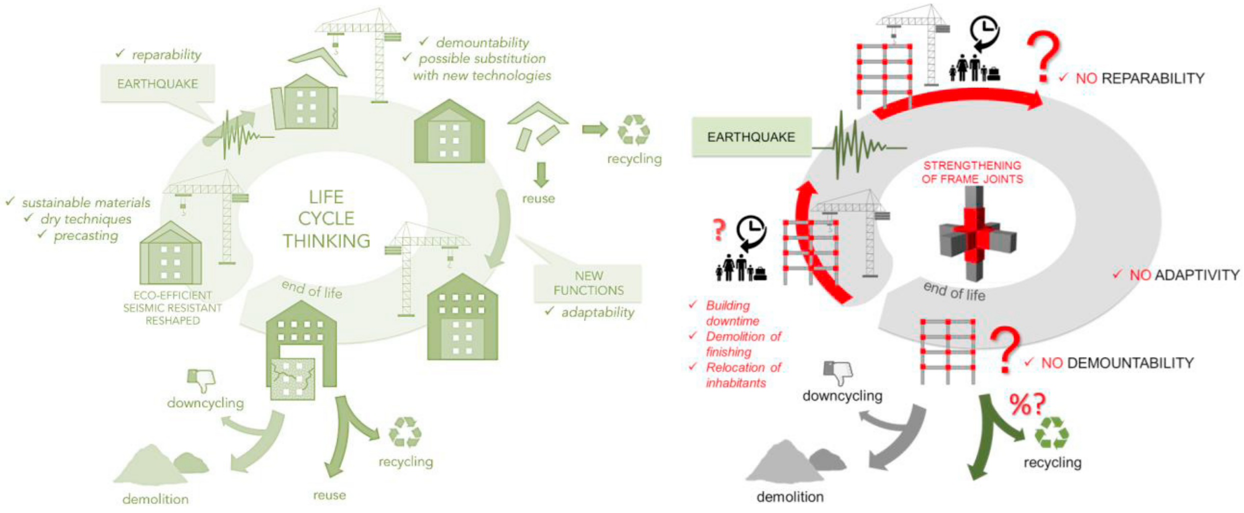


Fig. 1. Different approaches for the design. (a) Design approach at time of construction considering the sole construction phase. Current uncoupled design practice considering construction and operation phases: (b1) eco-efficient design of the energy retrofit; (b2) structural retrofit disregarding eco-efficiency; (c) next generation LC-based design approach for the renovation, considering construction, operation and end of life.

Structural retrofit, often carried out in emergency situation only, is also designed considering the sole operational stage to guarantee safety in the case of extreme events, such as in the case of an earthquake. The design is carried out by addressing modern and quite effective but very sectorial structural codes, whose application may result in safe and resilient but rather unsustainable interventions (Figure 1.b2). For example, damage control, reparability after an earthquake, end of life management are not mandatory parts of the design and the retrofitted building might require severe restoration after the seismic event, particularly to non-structural components, besides remaining energy intensive.

To overcome the major drawbacks of the uncoupled approaches, the concept of holistic integrated renovation was recently introduced. Holistic renovation concurrently tackles all building deficiencies, increasing the structural service life while pursuing safety, sustainability and resilience. Such a renovation strategy, requires a new and insofar missing approach that guarantees effectiveness of the renovation measures, also accounting for possible functional and mechanical interactions/interferences arising from different retrofit actions. Such an ambitious intervention can only be conceived by addressing a **Life Cycle approach**, where deep renovation actions are designed considering the whole life cycle of the retrofitted building, accounting for construction and operation phases as well as end of life (Figure 1.c).

When extending the reference time frame up to the entire life cycle of the building, **new principles** should be addressed in the conceptual design of the interventions (Figure 2a, Marini et al. 2017). In the **construction phase**, the pursuit of environmental, economic, and social sustainability would not only result in the selection of sustainable materials, in the reduction of the emissions due to transportation, and in the limitation of demolition interventions, but other mandatory issues should be considered: as an example, avoiding relocation of the inhabitants, by considering to operate from the outside of the building, and reducing the duration of the renovation works would minimize the impact of the intervention on the building users, thereby solving one of the major barrier to the renovation.



a) b)

Fig. 2. a) Life Cycle design for Sustainability and Resilience targets (adapted from Marini et al. 2017); b) re-evaluation of a typical structural retrofit intervention – the strengthening of the frame joints – under the new Life Cycle Thinking perspective

In the **operation phase**, additional requirements may be defined when addressing energy consumption, natural or man-induced hazards, and formal aspects. Under an environmental and energy point of view, CO_2 emissions should be cut by reducing energy consumptions, insulating the building envelope, exploiting renewable energy, etc. Under a risk-mitigation point of view, the structural behavior should be improved taking into account not only the protection of human life, but also the damage reduction of both structural and nonstructural components and the possible damage, e.g. by lumping it into few sacrificial components. Such additional targets would enable reparability of the structure, thus fostering resilience and reducing costs, building downtime and duration of the possible repair works after a major event. Regarding the formal aspects, the intervention should be conceived as to guarantee adaptability of the living spaces to possible future needs or destination changes, and ease of maintenance would substantially reduce costs and impacts throughout the operational phase.

Finally, the **end of life scenario** should be considered in the selection of the most appropriate retrofit technology option from the early design stages. Total demountability and possible selective dismantling of the retrofit system are critical characteristics as to reduce waste, down-cycling or landfill disposal, while fostering reuse and recyclability of the retrofit components.

All these new principles should be considered and applied from the early stage of the design, as to guide the designer's choices towards a more sustainable solution. Such features contribute to define a new expanded Life Cycle Thinking (e-LCT) approach.

3. Barriers and challenges to shift to a Life Cycle perspective

3.1. Barriers to operate the transition towards sustainability

In order to shift from a traditional design approach to the new envisioned LC perspective, many barriers should be overcome and new technical challenges should be issued. One of the major barriers to fostering sustainability of the existing building stock is the **mindset** of the actors involved in the renovation process. The envisioned LC perspective requires cooperation and multidisciplinary knowledge sharing among structural, energy and environmental engineers, architects and construction companies, who therefore need to overcome the common practice to selectively operate in their single field, in an inefficient manner. This principle, now embraced for the design of new structures since the introduction of the Building Information Modeling (BIM), is even more useful in the building renovation, for the multifaceted deficiencies that need to be contextually tackled. Furthermore, selection of the best retrofit option should no longer be based on the sole immediate economic effectiveness at the construction stage, but should rather be operated through multi-criteria decision-making tools, considering economic convenience together with other social and environmental issues along the retrofitted building life cycle.

Financial and social barriers should also be addressed and overcome. There is an urgent need to find new business models and retrofit strategies to increase the feasibility of the interventions. It is worth noting that the actual renovation rate is equal to about 1% (BPIE 2011), and it mostly relates to the sole energy refurbishment, while the structural retrofit is usually operated in emergency situations only. To overcome these major issues, some strategies have been recently studied. The most significant ones consist in the holistic renovation, the renovation carried out from the outside, and the incremental rehabilitation.

Holistic renovation, proposed by Takeuchi (2009) and Marini et al. (2017) among others, couples the benefits arising from energy and structural renovations in a unique intervention: tangible savings from the energy upgrade are reinvested to fund the structural retrofit; duration and costs of the interventions are reduced thanks to the shared construction site; long term protection of the investment is ensured by reducing the building damage or failure possibly caused by natural or man-induced hazard during the building service life. In Takeuchi (2009), Feroldi et al. (2013) and Marini et al. (2017), the concept of global **intervention applied from outside** was also proposed to overcome the main barrier to the renovation, which is associated with the need to relocate the inhabitants (BPIE 2011, La Greca and Margani 2018). Unlike other retrofit strategies, such as the local retrofit of the structural nodes, the adoption of an exoskeleton serving as seismic and energy retrofit measure does not require the demolition of the finishing, thus reducing costs and construction waste. Finally, the **incremental rehabilitation** (FEMA P-420 2009) is a recent approach in which the global retrofit performance objectives are achieved by implementing an ordered series of discrete rehabilitation action over an extended period of time, thereby reducing the initial investment and spreading the cost of the intervention over a longer time. The building target performance progressively increases with the completion of each rehabilitation step. Single rehabilitation actions can be integrated into ongoing facility maintenance and capital improvement operations, and careful design and staging can ensure continuous use of the construction or can reduce the building downtime. An example of holistic intervention carried out from outside and implementing incremental rehabilitation principles is presented in Labò et al. (2018), where the concept of "minimum initial step" solving the major vulnerabilities of the structure is also introduced. Besides these pioneering studies, more actions and research are required to boost the effective renovation of the existing building stock.

3.2. Technical challenges: new research needs

Some major research needs emerge in order to overcome the technical barriers to the application and spreading of a LC perspective in the renovation field: the development of a novel LCT-based design framework for the holistic retrofit, and the study of new holistic solution sets.

Introducing a LC perspective in the design of deep renovation interventions entails the adoption of a **new design approach**, which is quite far from current practice. A few attempts to produce sustainable design frameworks have been proposed in recent years that combine some but not all of the above aspects. Among others, Belleri and Marini (2016) and Wei et al. (2016) proposed a LCA framework combined with risk analyses, proposing methods to convert the seismic risk into CO_2 emissions and showing the convenience of risk mitigation in terms of reduction of environmental impacts. Vitiello et al. (2016) and Lamperti et al. (2017) combined LCA and Expected Annual Loss Analyses under a LCC perspective, thus producing a framework enabling the selection of the best retrofit option on the basis of an equivalent cost parameter. Calvi (2013) compared alternative seismic retrofit options based on the ratio between the difference of the building Expected Annual Loss before and after the retrofit and the cost of the intervention. Park et al. (2018) developed the Performance-Based Optimal Seismic Design with Sustainability approach that optimizes the structural solution adopting as objective functions the CO_2 emissions, the production costs, and the coefficient of variation of the inter-storey drift ratio.

To date, all the available frameworks are basically "ex-post" protocols, adopting different metrics and enabling comparative evaluation between possible renovation actions that were designed separately according to available sectorial codes. None is conceived to be adopted from the early design stage for the conceptual design of a renovation action that considers the multifaceted building needs, and none adopts an expanded Life Cycle Thinking approach also addressing the above mentioned additional principles (Fig. 2a). A next-generation design framework that enables the design of holistic retrofitting actions fostering safety, resilience, and sustainability is not yet available and represents a major challenge in the renovation field. Such a framework should be multi-disciplinary and would overcome the weaknesses and drawbacks of traditional, uncoupled approaches. Starting from the assessment of the building multiple needs in its as-is situation, it should enable preliminarily selecting different possible solutions targeting interdisciplinary and e-LCT performance objectives. Then, the selected solutions should be designed considering quantitative, multi-disciplinary targets. Finally, the best solution should be identified by means of multi-criteria decision-making tools.

The development such a framework requires the update and enhancement of common design tools, such as structural and energy Performance Based Design (PBD), as well as Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) procedures. As an example, performance levels established in the structural PBD should be redefined under a multi-criteria perspective: besides the protection of human life, damage should be controlled in order to limit the impacts along the building life. To date, the operational and immediate occupancy performances are mainly intended to ensure the operability of the building as to reduce the downtime costs; while in this new perspective, the focus would shift to the reduction of the impacts along the building life cycle. Seismic performances of non-structural elements should thus be considered, functional and mechanical interferences arising from different retrofit actions should be addressed and new targets should be defined as to protect such elements from damage (i.e. the inter-storey drift should avoid early damage in the new thermal envelope in the case of small amplitude earthquakes Passoni et al. 2018). LCA and LCC procedures should be updated to include hazard risk, thereby shifting from a static to a stochastic approach. Some preliminary attempts to include seismic risk into LCA procedures are presented in Belleri and Marini (2016) and Wei et al. (2016), which calculate the impacts connected to seismic risk on the basis of seismic losses evaluated with a PEER-PBEE and HAZUS methods, respectively; another framework is included in FEMA P-58-4 (2012). Validation of these methods at building and urban scale and the integration with the principles of e-LCT are still required.

The LC perspective and the new holistic design framework would establish the new qualitative multiple criteria and quantitative metrics to be addressed to assess the effectiveness and actual sustainability of existing and new solutions. Common practices may be found as unsustainable and might require redesign or enhancements; dismissal of some techniques could be envisioned in favor of new solution sets. As an example, the common seismic retrofit of RC frames, obtained through either strengthening of selective frame bays, or strengthening of the frame nodes may pose some problems related to the impairment of the finishing, while also requiring relocation of the inhabitants and long duration of the retrofit works, besides being non-compliant with the reparability and demountability requirements (Fig 2b). On the other hand, by introducing fast assemblage and easy disassembly, along with sustainability, among the mandatory targets of the retrofit, the development of new off-site light prefabricated components, could become critical to increase the cost effectiveness, the quality and timing of the construction project. Dry-assembly on site could also reduce waste and improve health and safety of the construction site. Standardized connection and modularity would facilitate selective dismantling and reuse of the retrofit components at the end of life; while favoring substitution/reparability after a seismic event, thus reducing downtime and waste.

To facilitate reparability in the operation phase, lumping the damage into sacrificial and easily replaceable elements was proposed. Some distinguished examples are: braced frames with controlled rocking and energy dissipating fuses (Deierlein et al. 2011, Gioiella et al. 2017), hinged walls with dissipative elements at the base (Belleri et al. 2016, Qu et al. 2016), shear links for eccentrically braced steel frames (Mansour et al. 2011).

The reduction of the impacts during the operation phase may be obtained from solutions that combine energy and structural upgrade. Exoskeleton applied as an energy-structural second skin in adherence or in close proximity to the existing building were recently proposed. Different technical solutions were proposed for RC buildings, featuring shear walls, shell or diagrids made of either steel (Takeuchi et al. 2009, Misawa et al. 2015, Labò et al. 2018, Marini et al. 2017), or timber sandwich panels (Susteric and Dujic 2014, Della Mora et al. 2015).

Finally, continuous building use may be enabled by interventions carried out from the outside, such as those proposed by Takeuchi et al. (2009) and Marini et al. (2017). Feasibility of such interventions require critical assessment and more research about the in-plane capacity of the existing floors, the connection between the new and existing structural elements, the capacity and protection of the stairwell walls and of the existing foundation system.

4. Concluding remarks

The transition toward a low carbon society can only be pursuit by reducing the substantial impact associated with the built environment and the construction sector, through systematic renovation of the existing buildings. In this paper the point is made that, to effectively reduce the environmental, economic, and social impacts, the renovation must be carried out by extending the design time-frame to the whole building life cycle, contextually addressing construction, operational and end of life phases. Under a LC perspective, the major drawbacks of the current uncoupled renovation practice are immediately apparent: structural retrofit carried out according to modern codes, may result in retrofitted buildings that are safe and resilient but rather unsustainable and still energy intensive; while energy efficiency measures carried out disregarding structural vulnerability may result in buildings that are unsafe with respect to even low-intensity earthquakes, thus resulting both unsustainable and non-resilient. Indeed, a LC perspective emphasizes the need to shift to an integrated holistic renovation approach, addressing the multifaceted needs of the building, conjugating structural retrofit, architectural restyling and energy efficiency measures. That in turn requires strong multidisciplinary competences and the synergistic work of researchers from different area.

Introducing life cycle thinking principles would completely change the conception of building renovation, redefining qualitative and quantitative performance objectives, design targets and principles, thereby re-directing research in the construction sector and boosting the design of new integrated retrofitting techniques. Sectorial codes and design methods should be replaced by a new LCT-based design framework, conjugating the principles of sustainability, safety and resilience. Such a framework would consider the building as a whole and would carefully assess and optimize its performances in each stage of the life cycle from a multi-sectorial perspective. Besides the use of eco-compatible materials, and renewable resources, additional criteria would define the retrofit design. Reparability, ease of maintenance, adaptability, selective dismantling, demountability, recyclability and reuse at the end of life would become mandatory features of the retrofit solution. This new perspective would also affect the decision making process. Minimum environmental footprint and cost over the life cycle, minimum building downtime, no need for the relocation of the inhabitants, reduction of the duration of the works and demolition waste management would serve as guiding criteria when selecting the most appropriate strengthening solution.

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