Rehabilitation of public housing buildings in a life cycle perspective

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Abstract. Planning the life cycle of a building, that is designing its resilience, is progressively increasing its relevance: the rehabilitation is considered a sustainable approach to the performance improvement of the built patrimony, which enables the extension of the useful life, compared to the more radical intervention of demolition and reconstruction. The most relevant aspects related to building performance regard the seismic rehabilitation of structures and the energy retrofitting of envelopes and installations. However, these are invasive and economically relevant interventions, that a private investor unlikely faces without specific normative or economic inputs. For this reason, the rehabilitation of public buildings and, particularly of public housing assumes a leading role in the building sector. The integrated approach of deep renovations leads to new strategies of life cycle planning and management based on the identification of environmental performance indicators with the goal of evaluating intervention alternatives, balancing the two – seismic and energy – strategies. An innovative approach to the seismic and energy rehabilitation of public housing in the Mediterranean area has been studied in the European research project Pro-GET-onE, coordinated by the University of Bologna. The research is based on the realization of an experimental exoskeleton to improve the combined seismic and energy performances. The solution also generates an economic surplus as a consequence of the increased living surfaces. This paper reports some results of the Life Cycle Assessment and the Life Cycle Cost Assessment related to this project.

1. Introduction
In the European building sector the prevalent activity is currently the renovation of the existing built environment. This is derived not only from the present demographic stagnation or from the actual urban policies on land preservation and valorisation, but also from the progressive economic and functional feasibility of rehabilitation projects. The interventions are generally divided into deep and shallow renovations. Deep renovations bring strong consequences on building performances, leading to actual standard levels, while shallow renovations are satisfied with simple improvements in respect to the previous levels [1]. The second type of interventions usually follows simple functional goals with mainly aesthetic targets.

Each year 1.2% of buildings is renovated in Europe, either deeply or softly [2]. Within this percentage the cases of deep renovation are still residual; in this respect the compliance to the regulation is consid-
ered a fundamental aspect, in order to increase the commercial value of the buildings [3]. In fact, reaching the compliance level requires an implicit medium long term vision: deep renovations are carried out with expected payback times longer than 10 years and confide in the idea that the plus-value of the final object compensate the initial investment. However, for little interventions – for instance, envelope insulation, windows or heat generators replacement – the payback time is determinative: only the investments with a relatively short payback time are taken into consideration. According to the research Episcope [4], financed by the Polytechnic of Turin, in the last twenty years around 10% of the buildings in the Piedmont Region was renovated for energy purposes, but only 2% of this percentage concerned global rehabilitations.

Furthermore, in absence of clear and significant structural deficiency, the interventions for the seismic safety of the building, are even more uncommon, because they are expensive in terms of initial costs and considered not strictly necessary. Therefore, for this kind of interventions it is not possible to think in terms of payback time. In fact, their convenience cannot be quantified, because it corresponds to potential damages to persons and things with very long prevision.

The intentions of private investors are often halted when initial costs are considered too high and in any case unnecessary. From this point of view, public investments on strategic buildings should be decisively superior to create an increased culture of safety and compensate the common hesitancy. In some cases, it is possible to think about the so-called ‘interventions with opportunities’, that is interventions that try to bring together investments with low payback time – soft renovations, for instance for energy purposes – and additional investments in safety and prevention. In the case of public investments, cost analysis (LCCA) or environmental impact analysis (LCA) can support decisions on these integrated renovations [5]. Finally, in a life cycle perspective, interventions can be seen not only as an economic opportunity but also as a way to use buildings more safely, more comfortably and, in general, with more quality according to the current augmented needs [6].

2. LCC and LCA for housing buildings

Life cycle planning is of capital importance for deep renovation projects of public housing. Life cycle analysis can be cost oriented in the Life Cycle Cost Analysis (LCCA) approach, or environmental impact oriented in the Life Cycle Analysis (LCA) approach [7]. In both cases Key Performance Indicators (KPIs) are needed to compare different strategies and design options in the life cycle planning stage [8] (ISO 15686-1: 2011 – Buildings and constructed assets – Service life planning – Part 1: General principles and framework).

Life cycle planning and design of building durability aim at proofing that building shelf life after construction can last the time requested by building technical regulations and contract requirements. The goal of life cycle planning is also to reduce operation costs and facilitate maintenance activities. Shelf life of a product or a building is the time period after installation or construction during which requested performances are fulfilled. Since life cycle planning is based upon a forecast of future performances of the building, approximations are allowed.

In life cycle planning the following aspects are entailed:

a) Probable performances of building components, considering the expected use conditions and external environment;

b) Building systems construction step;

c) Building systems costs and environmental impacts in life cycle study period;

d) Operation and maintenance costs;

e) Needs of restoration, replacement, dismantlement, removal, re-use and disposal, and related costs.

Shelf life duration is difficult to estimate and depends on the following components: environmental exposure, performance of components in forecasted conditions, quality of components, products and connections and actual use and maintenance. Data acquisition is usually not an easy task. The proposal of ISO standard 15686-1 is to obtain the necessary information from analysis of similar buildings, analysis with factorial method or tests of accelerated ageing exposure [9] [10].
The 2010/31/EU Energy Performance Building Directive (EPBD) and regulation 2012/244/EU introduced the Life Cycle Cost Analysis approach and the Global Cost method for the cost evaluation of buildings. The EU regulation is based on the European standard EN 15459. Some differences can be found from the approach of the ISO 15686-5:2008. In fact, the international standard defines the global cost as the “Whole-Life Cost” (WLC), i.e. the total cost that entails all the significant and relevant costs, including benefits and cost/revenues that are not directly due to the building itself, as for instance financial costs, incomes from sales and rents, operation costs and external costs. The EN 15459, instead, defines the Global Cost as the total amount of costs generated by the building during its life cycle. The financial level analysis is very similar to the one of the international standards, and costs are only referred to the owner. The macroeconomic level analysis, instead, introduces the cost of the greenhouse effect, because the social impacts of the building must be evaluated. The cost of greenhouse effect is the estimate, in terms of money value, of the environmental damage caused by CO₂ emissions generated by the heating and cooling system of the building during the study period [11].

The Life Cycle Assessment (LCA) aims at evaluating building sustainability with a parallel approach. LCA evaluates inputs, outputs and potential environmental impacts of a product system during its life cycle. Life Cycle evaluation is based upon four steps defined by international standards (ISO 14040:2006): objects definition and system boundaries, inventory analysis, impact assessment and understanding of results.

The Life Cycle Inventory Analysis (LCI), is the fundamental step of LCA; ISO 14040 defines LCI as the calculation of the input and output flows through system boundaries. The aim of LCI is to examine a set of elements for each step of the production process and of the life cycle period, mainly the following: primary energy (MJ) renewable and non-renewable, electric energy (computed considering the national energy mix), consumption of combustible renewable and not renewable resources, renewable and not renewable raw materials, recycled resources, solid wastes.

Data gathered in the LCI step are then evaluated to quantify environmental impacts. ISO 14044 describes the approach for the quantitative evaluation of impacts related to the flows identified in LCI. These impacts are classified on the base of category indicators, i.e. indicators that represent impacts caused by resources consumption for input flows, and impacts caused by emissions for output flows. The LCA approach usually considers the following three impacts: human health, quality of ecosystems, and resource consumption. Environmental impact evaluation is based upon the weighting of the elements of the analysis with the aim of highlighting the effects of a substance on the environment or on human beings. In this step the assessment procedure transforms objective data (concerning the quantity of a substance) into an evaluation of an environmental hazard and a potential damage. Therefore, it is the weighting procedure that indicates the relative importance of single effects of the components on the environment.

The two approaches, LCC and LCA are often integrated in literature, with the aim of better supporting life cycle planning decisions with multiple indicators [12] [13]. In a life cycle planning perspective, the weighting of LCC and LCA indicators is of major importance compared with the weighting of the single impacts of products.

3. The Pro-GET-One research
The European research project Horizon 20-20 titled Pro-GET-onE (Proactive synergy of inteGrated Efficient Technologies on buildings’ Envelopes) identifies a unitary strategy for the energy retrofitting and seismic rehabilitation of public housing, according to the priorities and the expectations of the users [14]. The University of Bologna is coordinating this project, which has 15 partners in various European countries. The research has started in May 2017 with the analysis of some case studies in Italy, Greece and Romania and will be ending in 2021 with a real intervention in Athens, for a total cost of almost 2 million Euros.

The idea of the project is based on the integration of different technologies to reach high performance levels in three fields:

1) Energy requirements, adding new prefabricated and efficient plug and play components and HVAC systems;
2) Structural safety, using external elements to improve the structural capacity of the building, hosting the above mentioned building components;
3) Social sustainability, raising the value of the buildings and the attractiveness of the retrofit options and offering personalized solutions to users, owners and managers.

Within the perspective of obtaining maximum compatibility with the existent buildings and minimum invasiveness, the strategy tends to improve the overall structural resistance of the building but operates locally on the remain vulnerability, minimizing invasive interventions. Trying not to force the inhabitants to leave their dwellings for a long time, it has been decided to test a new system of metallic elements (GET-System), connected to the existing structure and properly dimensioned, in order to reduce the horizontal displacements and contribute to the building ductility. The goal is to improve the structural performance by at least 1 seismic class. The GET-system is composed by a metallic exoskeleton, a thermal envelope with additional space, an insulated roof, energy systems to cover heating and cooling and DHW needs (heat pumps in this case), a decentralized ventilation system and PV panels on the roof (Figure 1).

![Figure 1. Pro-GET-onE, section of the preliminary project, with façade additions and detail of the modular system with installations and envelope. 1. Distribution system; 2. Façade addition (GET-system); 3. Raised part; 4. Centralized heat generator; 5. Air Conditioned space; 6. Installations.](image1.png)

![Figure 2. Pro-GET-onE, perspective view of the preliminary project, with façade additions and detail of the modular system with installations and envelope. 1. Photovoltaic system; 2. Opaque envelope; 3. Transparent envelope; 4. Adaptable façade system; 5. Installations; 6. Main structural elements.](image2.png)

![Figure 3. Structural conception of exoskeletons.](image3.png)
The new structures don’t require invasive operations and the installations need relatively small foundations. A very delicate issue concerns the connection between the existing reinforced concrete frame and the metallic structure. The new external structure (exoskeleton) hosts also the installations required for the energy retrofitting and represents a design instrument to improve the attractiveness of the façade, fulfilling the requests and the needs of the users (Figure 2).

There are some European examples of technological solutions that employ exoskeletons for the recovery of existing buildings (Figure 3). Among these, it is worth mentioning the Tour Bois de la Prêtre in Paris, by the architectural firm Druot, Lacaton and Vassal, the condominium in Aalborg by Møller Architects and the tower in Winterthur, by Burkhalter Sumi Architekten. None of the towers employs seismic structures, hosting at the same time building components and installations to reduce the energy consumption [15].

Since energy consumption during the usage phase, after retrofitting, is significantly reduced, both in summer and in winter (sun shading devices), the embodied energy of the components and the energy used for disposal and recycling become very important. Therefore, in LCA and LCC analysis the quantity of materials used for the seismic retrofit acquires a prevailing role: in fact, the reduction of the seismic vulnerability is inversely proportional to the amount of structural mass utilized for the exoskeleton and, consequently, to the total environmental impact. The final goal of the LCA and LCC analysis is definitely to compare the environmental impact of the measures for seismic safety and the impact of the components utilized for the reduction of energy needs down to near zero. In the case of Pro-GET-onE, three alternatives have been considered for the exoskeleton: a steel structure, an aluminium structure and a CLT structure.

**Figure 4.** Components within GET-System. The Athens case study is represented in the picture to the right.

4. **LCA and LCC for the Athens case study: methodology and results**

4.1 **Life cycle environmental assessment (LCA)**

At this stage of the research the first results of the Environmental and Cost Assessment of the GET-System in the framework of the case study of Athens (Figure 4) are reported below. The goals of the environmental assessment were two: to compare the alternatives in some of the options for the GET-System and to assess the GET-renovation approach versus a demolition + new built approach, in order to provide information for future decisions.
The assessment has followed the main guidelines of LCA studies, even if a fully ISO-compliant study still needs to be completed with reference to the final specific data from the renovation project. The inventories (LCI) have been built at a higher level by an Excel file, and a more specific level through the OpenLCA software, by including datasets from Ecoinvent database. For most of the materials, the inventory analyses of building components were built with Ecoinvent database. When a material or its equivalent was inexistent in this database, the information was retrieved from scientific papers. Since reference databases and literature have supported the study in this phase, it is not possible to state that the full environmental study is completely in line with the corresponding ISO standards.

The scope of the performed assessment was cradle to grave. However, for the specific studies per product or element, the operational phase and part of the deconstruction were not included. This is because all data are depending on other building components. For this reason, it is not possible to disaggregate them during this phase. Besides, these are optional steps in LCA studies according to Environmental Product Declaration guidelines (Figure 5). Therefore, the operational phase was limited to the whole building approach and the PV systems.

![Figure 5. Mandatory and optional elements for construction products according to 15804 and 15978 EN standards (Source: BRE Briefing paper 2016).](image)

The selected impact assessment was the method ReCiPe 1.11 (Dec 2014) Midpoint Hierarchist, even if the focus has been put on the Global Warming Potential category (GWP) [16]. The environmental assessment has followed the iterative steps considered in the ISO standards.

Firstly, some partial studies were performed. The Functional Unit (FU) was specific for each assessment. The alternatives were the following: steel or aluminium for the exoskeleton, aluminium or wooden elements for the façade panels, various options for thermal insulation.

The exoskeleton is one, if not the most, relevant element of Pro-GET-onE. Its function is to provide earthquake proof structural reinforcement. In addition, it supports all the other elements of the refurbishment, namely the envelope and the products that improve the energy efficiency of the building to align it to the nZEB concept. Two different scenarios have been modelled in order to better evaluate the
environmental impact and to provide guidance on the selection of the most appropriate material for this structural element:

1) aluminium exoskeleton: whole structure – pillars, beams, connections, braces – and slabs made from aluminium.
2) steel exoskeleton: whole structure – pillars, beams, connections, braces – from steel and slabs made from aluminium as in the previous case.

Two scenarios for the modular façade were assessed from cradle to grave. The baseline case is composed by an aluminium cassette, two aluminium perforated plates, a layer of cross-laminated timber (CLT) and an aluminium profile, according to the solution proposed by the consortium (Figure 6). The alternative group comprises a layer of CLT as internal cladding, a layer of outdoor plywood, two panels of gypsum and a profile of glued-laminated timber (glulam). The functional unit for the environmental assessment of both solutions is a sample of 1 m$^2$ of the group of layers. CLT was modelled as glulam once it does not exist in Ecoinvent but it is manufactured from the same raw materials and involving the same producing processes as glulam.

Regarding the energy systems, the proposed solutions for the GET-System are based upon the offer of products from the partners of the project: Multifunctional Roof Edge by Anergdy, Elfopack by Clivet and Aircare by Savio-Thesan.

![Figure 6. Floor unit: timber slabs pinned to two lateral steel profiles to be fixed to the steel frame.](image)

The Anergdy Multifunctional Roof Edge (MRE) product is a rooftop-mounted module with crystalline silicon photovoltaic panels or with the combination of photovoltaics and wind energy, depending on the desired version of the module. In the case of Athens case study, the standard solution with only photovoltaics is chosen for its implementation. The functional unit is one MRE C05 module, with a weight of 172 kg, from which 85 kg are from steel, 84 kg from PV panels, and 3 kg correspond to the inverter.

The Clivet ELFOPack product is a multifunction heat pump unit for stand-alone systems that simultaneously meets the demand of heating, cooling, dehumidification, production of domestic hot water, and controlled mechanical ventilation with thermodynamic recovery and electronic filtering. The functional unit for this LCA is one single ELFOPack heat pump, with a dry weight of 290.80 kg including its packaging, from which 184.2 kg are from stainless steel, 57.1 kg are from different kind of polymers (mainly polypropylene and polyethylene), 20.7 kg are from aluminium, 9.5 kg are from copper, 7 kg
correspond to the wood pallet, 5.5 kg are from the inverter and other electronic components, and the rest form other materials.

The Savio Aircare ES is an energy recovery ventilator responsible for air renovation, meant to be installed in an exterior wall. It removes stale air from the inside while inserting fresh air from the outside after being properly filtered and collecting heat recovered from the exhaust air. The functional unit considered for the environmental assessment was one Aircare ES unit at the gate of the manufacturer’s factory. The appliance is divided by groups of components by proportion to its total weight.

The assessment has been done with two parallel goals, in view of suggesting improvements for the providers and supplying in-hand data for the whole building assessment.

Regarding the comparison between the aluminium structure and the steel structure, the results indicate that the exoskeleton made in aluminium results more impacting in all the categories excepting one, with an important difference in the Climate Change category. The wood fibre insulation appears to be the most advantageous option in terms of GWP. As for the façade panels, flooring options and windows, partial results indicate that wooden solutions are the most favourable. GWP for the wooden windows is 68312.7 kg CO₂e, compared to 286667 kg CO₂e for the aluminium windows.

With regard to the energy systems, the PV system from Anerdgy is very competitive in terms of GWP compared to existing studies. For one MRE C05 module, the GWP of baseline scenario (cradle-to-grave with world origin) is 233 kgCO₂e, much below the GWP of 2095 kgCO₂e cradle-to-gate scenario due to the positive impact of renewable electricity production throughout 30 years lifetime. Ventilation system designed by Savio is already well optimized and little improvement margin is left. Finally, the heat pump Elfopack has a weak point because of the refrigerant, that is having a great influence on the overall environmental performance of the product.

In general terms, the GET-renovation in Athens has an estimated GWP of 1000 tons of CO₂e for a period of 100 years, whereas for a period of 50 years it is around 700 tons of CO₂e. For a period of analysis of 100 years, the windows, the exoskeleton and the PV installation are the most impacting components of the GET-System. Wooden windows are recommended to reduce the impact. For a period of analysis of 50 years, the exoskeleton is by difference the most impacting component of the GET-System. The average value of 1000 kg CO₂e/m² (Figure 7) for a cradle-to-grave approach appears to be a realistic assumption for the current comparison, however other studies give lower values (Figure 8, Figure 9) [14].

For the whole building assessment, the baseline scenario is the demolition and construction of a new building with the same safety and energy performances. The Functional Unit is 1 m² of seismic safe nZEB over 50 years. The whole building assessment shows that the GET-renovation scenario is clearly impacting much less CO₂e emissions than demolition and new built, and even less in the case of maintaining the building almost as it is.

For a period of 100 year, Get-renovation is impacting 70% of the assumed baseline (1332 vs 1840 kgCO₂e/m²·y) and 24% of the status quo situation (1332 vs 5550 kgCO₂e/m²·y). For 50 years, GET-renovation is impacting 55% of the assumed baseline (713 vs 1300 kgCO₂e/m²·y), and 25% of the status quo situation (713 vs 2850 kgCO₂e/m²·y).
4.2 Life cycle costing assessment (LCC)

The lifecycle costing assessment is directed by two main goals: to identify the most price-impactful cost categories and identify critical costs, allowing possible strategies to decrease or control the LCC costs; to point out the advantages of investing in renovating a building when compared with the possibility of demolition and reconstruction following the guidelines of a seismic-resistant and nearly Zero Energy Building (nZEB).

A dedicated LCC tool has been developed in the framework of the project using an Excel spreadsheet supported by macros, which considers the main cost categories indicated in the reference standards (ISO 15686-5 and EN 15459) and in the EU Directive 2014/24/EU. This tool includes the main influencing parameters (related to the building, the energy use, financial aspects and other), in order to obtain a high
number of results according to different scenarios. Critical parameters are: energy price escalation, discount rate, steel exoskeleton investment (which accounts for 16% of construction costs), building lifetime. According to ISO 15686-5, the results are given using the Net Present Value (NPV) calculation.

The sensitivity analysis is one of the techniques suggested by the standard ISO 15686-5 to indicate the uncertainty and risk associated to the LCC analysis. The parameters considered for the sensitivity analysis are the period of the analysis, the real discount rate, the inflation rate, process variation, energy price escalation. The periods of analysis were chosen based on literature values and own experience. The real discount rate, the inflation rate and the energy price variation are based on data collected from Eurostat. The range of prices variation is based on the examination of market values and own experience.

The next graphs allow understanding how the costs are distributed by category and along the period of analysis (Figure 10).

![Graph showing cost distribution](image)

**Figure 10.** Distribution of costs by category and along the periods.

The 18 scenarios presented concern all the possible combinations of the parameters that affect these particular results: the period of analysis (due to energy, maintenance and replacement costs), the price variation and the yearly escalation of the price of electricity. Two categories of costs stand up: building materials and works and electrical costs. The preponderance of each of them depends on the scenario.

For the EU scenario (without real estate value increase), it can be stated that for the Athens pilot building, over 50% of the assessed scenarios outcomes foresee savings between 4 M€ and 6 M€ when choosing the GET-renovation over the demolition and new built option. When analysing the GET-renovation as a percentage of the demolition and new built option, the median value is around 50%.

For the Greek scenario (including real estate value increase), it can be stated that most of the assessed scenarios outcomes foresee savings between 1 M€ and 3 M€ when choosing the GET-renovation over the demolition and new built option. When analysing the GET-renovation as a percentage of the New
Built solution, the median value is around 75%. The median value of the LCC for the GET-renovation in the different scenarios, including the real estate value increase, is 5 M€.

As regards the cost categories, when a lifetime of 25 years is considered, building materials and works are the most influencing costs, whereas for 100 years horizon electricity consumption costs are dominant.

As for the energy payback, in more than 50% of the calculated scenarios, the achieved energy savings pay back the investments and maintenance costs of the GET-renovation such as designed for the Athens pilot building comparing to maintaining the status quo. When considering a 100 years horizon, 75% of results are positive in terms of energy payback. Nevertheless, the results are highly dependent on the considered building lifetime and energy prices escalation, as well as on the actual energy consumed. No important deviations on the energy consumed are expected but low energy consuming buildings are very sensitive to building operation and occupants’ behaviour, so it is important to take care of these aspects to promote the expected economic results.

5. Conclusions

An innovative approach for building deep renovations has been presented, integrating seismic rehabilitation and energy retrofit. Both the environmental and cost assessments have been carried out following referenced methodologies and standards. The goals of the environmental assessment were to compare the alternatives in some of the options for the GET-System and to assess the GET-renovation approach versus a demolition + new built approach.

In general terms the whole building assessment shows that the GET-renovation scenario is clearly producing much less CO2e emissions than demolition and new built, and even less in the case of maintaining the building almost as it is. As for the energy payback, in more than 50% of the calculated scenarios, the achieved energy savings pay back the investments and maintenance costs of the GET-renovation such as designed for the Athens pilot building, comparing to maintaining the status quo.

However, results might have an important variation. This fact is due to the type of study, with a big number of elements and data, which are not known accurately enough. Availability of data is a typical barrier in this kind of studies, in addition to the type of project (innovation project), which increases the challenge. In addition, the baseline scenario (a new building) is estimated through existing sources, but there is not a specific design for the purpose of the studies (out of scope of the project). Therefore, the results and conclusions might vary in the following steps of the research according to these exposed limitations.

Finally, methodologies and data do not allow the full appreciation of the extra-benefits related to the proposed renovation approach. Co-benefits of the GET-renovation, such as better health (improved air quality, thermal comfort, lighting, avoided injured), better safety (avoided damage, lower insurance tax, higher building value), increased space and improved aesthetics have been identified and listed but most research to quantify them in economic terms (in order to be included in a LCC approach) is still to be done in a general framework. Limitations have been encountered to quantify the economic and social value coming from the safety improvement, the improved indoor quality and the low environmental impact obtained with the renovation, which is directly benefitting the occupants and the society as a whole.

This is not a specific barrier for this project, but for all the long term investments that contribute to other gains, vis-à-vis the ones that are quantifiable in terms of current economic calculations.

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