Advances in Modelling and Analysis A
Vol. 55, No. 3, September, 2018, pp. 158-164
Journal homepage: http://iieta.org/Journals/AMA/AMA_A

Supporting decision methodology for the refurbishment of buildings: Optimization in nZEB perspective

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https://doi.org/10.18280/ama_a.550309

Received: 6 April 2018
Accepted: 12 June 2018

Keywords:
nearly zero energy building, cost-optimal, multi-objective optimization, retrofit

ABSTRACT

The improvement of the performance in building sector is recognized as one of the major action to meet the requirements for a sustainable future. Over the years much progress has been made for this aim. Nearly Zero Energy Building (nZEB) and Cost-Optimal approach are common concepts in design and refurbishment phase of buildings. In particular, the Cost-Optimal allows the definition of the best solutions by coupling energy and economic analyses. Nevertheless, between similar results from energy efficiency and costs point of view, other variables should be evaluated for retrofit interventions of buildings, considering for example such as environmental aspects. Several techniques are available for coupling all these aspects in an overall assessment perspective of building behavior. Among them, the Multi-Objective Optimization (MOO) is suitable for this purpose.
In the present paper, through thermo-dynamic simulations, MOO is applied to the cost-optimal solutions of a real residential building in a nZEB perspective in order to define the best refurbishment hypotheses,
Crossing the Cost Optimal analyses with other meaningful variables: fixing two objectives, like the minimization of users discomfort and the incorporated CO_2 in the refurbishment materials, up to 10 variables that can be analysed in the same simulation.

1. INTRODUCTION

Buildings are responsible for about 40 % of total energy consumption -and correspondent operational CO_2 emissions- in Europe [1], and about 75 % of them are energy inefficient [2].

The document presented by the European Commission staff on November 30, 2016 [2], represents a comprehensive summary with the following main targets concerning 2030 energy and climate goals:

(1) increasing the share of renewable energy consumption to at least 27 %;

(2) reducing Greenhouse Gas Emissions by at least 40 % below 1990 levels;

(3) achieving energy efficiency at EU level of the 30 % binding target;

(4) improving electricity interconnections between Member States.

During the last decades, the most meaningful approach - the Zero Energy Buildings - has defined different set of specific rules thought to strongly reduce the energy consumption of buildings and their environmental impact in terms of GHG emissions, supporting the improvement of energy performances of buildings and, at the same time, the diffusion of solutions involving renewable energies. The concept of Zero Energy Building was born in this context in the early 2000's [3] and it has been consolidated as the standard reference for all the aspects concerning the balance between needs and self-sufficiency for a building in its operating conditions.

Some worldwide initiatives, moving from the Task 40 of the International Energy Agency (IEA), have ensured a rapid diffusion and evolution of the ZEB concept, both in terms of declinations and real applications [4]. The last definition of ZEB performance is represented by an innovative approach in which buildings are considered under a holistic vision that integrates energy, environmental and economic analysis, closely related with the built and natural environment and the end users [5].

Many of the energy related policies have their focus on new buildings but the majority of the existing building stock has more than twenty years and presents low energy performances. Most of these buildings may not be able to reach the new energy standards due to design and construction constraints and to the lack of information and the limited access to capital to face the high investments required and the long pay back times besides the age of the buildings [6]. The IEA-EBC Annex 56 project "Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation" developed, as basis for future standards, a methodology related to building renovation for maximizing effects on reducing operational carbon emissions and primary energy use while taking into account the cost-effectiveness of the related measures [6-7]. Additionally, it focuses on the overall added values achieved in a renovation process, which means to identify the global quality improvement and further additional benefits (here called co-benefits) like comfort improvement (thermal, natural lighting, indoor air quality, acoustics, etc.), that allow increasing the value of the building [7]. The Directive 2010/31 UE (EBPD) introduced the "Nearly Zero Energy Buildings" linked to cost optimality, where energy benefits are related to economic benefits. The "Cost Optimality" methodology is applicable both to new and existing buildings, as introduced in the Regulation 244/2012 [8]. The Global Cost calculation in term of net actual value during a considered period is calculated according to the methodology of EN 15459:2007 [9-10], update to a new version in 2017 [11].

Concerning energy aspects, there are many tools and methodological approaches able to support designers to achieve ZEB goals, such as thermo-dynamic simulations, calculation programs with static balances [12], just to name a few. The same considerations could be done related to economic analysis and environmental ones, the first applying calculation methods such as pay-back time, life cycle-costing or cost-optimal [13], the latter evaluation methodologies as carbon footprint and life cycle assessment.

In a holistic and in an optimization perspective, both for new buildings and refurbishment design, the Multi-Objective Optimization (MOO) approach is currently considered as the more comprehensive and integrated solution for coupling all these aspects in an overall assessment perspective of building behavior. Metaheuristics methods, and among which genetic algorithms, have shown to be an appropriate way to deal with multi-objective issues such as environmental and energy performance [14-15]. Many strategies are available for the optimization of building energy performance by taking into account different algorithms and objective functions [16].

Dynamic simulation tools can integrate energy and economic aspect with co-benefits evaluations, like comfort and CO_2 emission. The co-benefits may be relevant or decisive for the added value brought by energy-related building renovation, but most times they are not considered in the decision-making process [17]. Co-benefits are not adequately perceived by the users benefitting from them or by the investors taking the renovation decisions [6]. These benefits are often difficult and nearly impossible to quantify and measure accurately, which makes it much more difficult to add their contribution into a traditional cost-benefit analysis [18].

2. METHOD

Since the importance to assess the effectiveness of potential solutions in a comprehensive manner [19], a more promising solution is to use a building optimization algorithm coupled with a simulation program to find an optimal solution [20]. Currently, simulation-based optimization has become an efficient measure to satisfy several stringent requirements of high performance buildings (e.g. low-energy buildings, passive houses, green buildings, net zero-energy buildings, zero-carbon buildings, etc.) [20]. The optimization approach is based on a computer model running a building simulation program coupled to an optimization engine. An iterative method driven by optimization algorithms progressively solves the analyzed problem. The solution is gradually approached until it is reached and it is established as the level that satisfies an optimality condition selected by the user [19].

Among the simulation methods [21-22], in the present paper, the dynamic simulations were carried out with Design Builder, the user friendly GUI for EnergyPlus. This software supports the optimization analysis with a specific module using a NSGA2 algorithm. Fixed two design objectives, the process continues until the Pareto Front shows the best design solutions in function of the design variables selected. Numerical analysis combined with Cost Optimal analysis permit to find that ones that more satisfy the priorities.

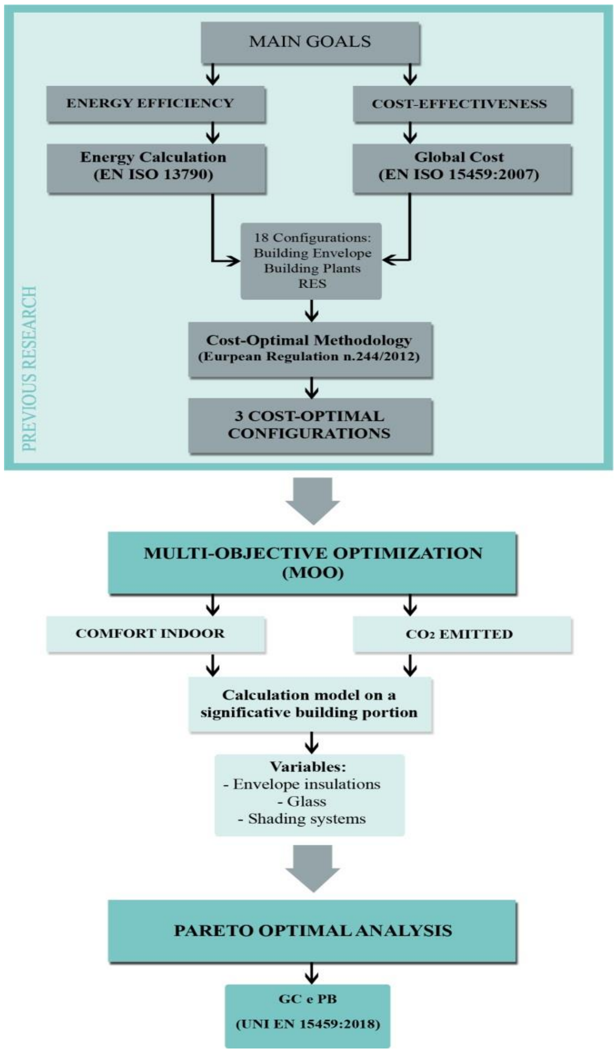

Figure 1. Methodology steps

The present research moves from a recent case study (Figure 1) published by Guazzi et al. [13] in which the refurbishment design of a social housing in the northern Italy was carried out through the 2012 cost-optimal methodology [23].

In this context, the energy efficiency was achieved applying the international standard EN ISO 13790 [24] to eighteen building scenarios in which different configurations of building envelope solutions, building plants and RES were combined. For each of the eighteen scenarios the energy consumption and the global cost were calculated following the EN ISO 13790 [24] and the EN 15459:2007 [25] respectively. Finally, the application of the Cost Optimal methodology [23] reveals that the most advantageous solutions combine district heating with medium or high insulation levels and a more or less PV panels surface respectively.

The current study was conceived to complete the previous research: The Multi-Objective Optimization method (MOO) is applied, through thermo-dynamic simulations, to the defined cost-optimal configurations in a nZEB perspective in order to achieve the best refurbishment hypothesis not only in term of energy efficiency and cost effectiveness, but also of comfort indoor and the reduction of the emitted CO_2.

The calculation model -the thermo-dynamic software Design Builder- is applied to a significant portion of the same social housing in northern Italy, varying envelope insulation thickness, windows characteristics and shading systems, following the scheme in Figure 1.

The optimal renovation scenario was analyzed in terms of Global cost and Payback period applying the EN 15459:2017 [11]. Comparing the output of the MOO analysis with the previous GC analysis, the intent of this research is to understand if the co-benefits need an extra-cost and if this could be justified [7].

3. CASE STUDY OPTIMIZATION

The methodology has been applied on an existing residential social housing (Figure 2), studied in the previous research [9]. The construction presents a "L" floor plan and three stairwells protruding toward the inner court that distribute the 30 small size residential units.

Figure 2. Existing building case study

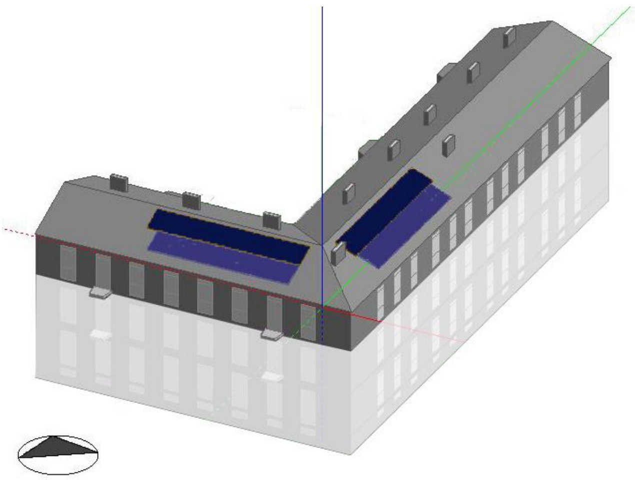

Figure 3. 3D-model of the case study building – third floor

After the validation of the model realized with Design Builder (Figure 3), the optimization analysis was applied on the third floor: it was a representative portion of the whole building but this permitted to reduce the running time of the simulation. The internal floor was set adiabatic.

To define the optimization problem, two design objectives were defined:

(1) Minimize operational carbon CO_2;
(2) Minimize discomfort hours (EN 15251 cat. II, [10]).
(3) The variables selected were:
(4) Insulation of the opaque envelope (walls and ceiling);
(5) Type of glass;
(6) Local shading devices;
(7) Window blinds.

Table 1. Variables configuration

Variables	Properties	
WI-10 to WI-24	S: 0.10 m - 0.24 m	U: 0.26 - 0.12
CI-12 to CI-24	S: 0.12 m - 0.24 m	U: 0.26 - 0.14
G-1	g: 0.597 TL: 0.769	U:1.37
G-2	g: 0.280 TL: 0.408	U:1.089
G-3	g: 0.474 TL: 0.661	U:0.776
G-4	g: 0.548 TL: 0.732	U:1.175
G-5	g: 0.423 TL: 0.568	U: 0.897
LS-1	Louvres + 0.5 overhangs + sidefines	
LS-2	Louvres 0.5 projection	
LS-3	Louvres 1 projection	
LS-4	Louvres 1.5 projection	
LS-5	0.5 overhangs	
LS-6	No shading	
WB-1	Blinds with high reflectivity slats	
WB-2	Blinds with low reflectivity slats	
WB-3	Blinds with medium reflectivity slats	
WB-4	Mid-panes blinds with medium reflectivity slats	
WB-5	Slatted blinds	

The values that the variables can take on during the analysis are described in Table 1. Insulation width varied with a step of 1 cm. Local shadings where applied on the south side of the building, while the windows blinds were applied to the whole building but only with the presence of people and in case of a solar radiation greater than 120 W/m^2.

The maximum number of generations determines the time and computing resources required to complete the analysis. Once examined that the solution has converged before the 20th generation and that enough optimal solution have been found, maximum number of generations was set equal to 20. Initial population size defines the different solutions that may exist within the same generation. In this case, the initial population size was set to 20.

4. RESULTS

The Pareto front represents the set of results of the optimization process after 238 iteration and it consists in 16 different configurations (red points, Figure 4) calculated with respect to two different design objectives: minimize both operational carbon CO_2 and discomfort hours. Table 2 shows a brief description of the Pareto front or optimal solutions.

Table 2. Description of the sixteen configurations of the Pareto front

Iteration	Glazing type	Local Shading type	Window blind type	Wall insul. width (m)	Ceiling insul. Width (m)
29	G-1	LS-6	WB-5	WI-23	CI-20
97	G-3	LS-1	WB-3	WI-22	CI-24
99	G-2	LS-1	WB-4	WI-24	CI-24
114	G-3	LS-2	WB-3	WI-23	CI-22
129	G-5	LS-5	WB-2	WI-22	CI-24
131	G-3	LS-5	WB-2	WI-23	CI-24
137	G-5	LS-6	WB-3	WI-23	CI-24
161	G-5	LS-5	WB-3	WI-22	CI-24
165	G-5	LS-6	WB-2	WI-23	CI-24
188	G-5	LS-1	WB-3	WI-23	CI-24
196	G-5	LS-2	WB-3	WI-23	CI-19
197	G-3	LS-1	WB-3	WI-24	CI-22
198	G-5	LS-5	WB-3	WI-23	CI-24
203	G-5	LS-2	WB-3	WI-23	CI-24
206	G-5	LS-5	WB-3	WI-23	CI-22
228	G-5	LS-1	WB-2	WI-23	CI-23

To identify the configurations that better balance the design objectives, a numerical analysis of the Pareto front configurations with respect to the correspondent values of both the operational CO_2 and the discomfort hours, was carried out.

Table 3. Percentage variation of the design objectives with respect to the minimum value

Iteration	Operational CO_2 (kg)	D % (min)	Discomfort hours (hr)	D % (min)
29	8,798	0.0	1,478	27.4
97	**9,169**	**4.2**	**1,199**	**3.4**
99	9,374	6.5	1,160	0.0
114	8,969	1.9	1,340	15.5
129	8,938	1.6	1,365	17.7
131	8,818	0.2	1,387	19.6
137	8,803	0.0	1,452	25.2
161	8,935	1.5	1,373	18.4
165	8,807	0.1	1,448	24.8
188	**9,178**	**4.3**	**1,196**	**3.1**
196	9,100	3.4	1,319	13.7
197	**9,121**	**3.7**	**1,201**	**3.6**
198	8,891	1.1	1,374	18.5
203	8,996	2.2	1,319	13.7
206	8,929	1.5	1,373	18.4
228	**9,198**	**4.5**	**1,196**	**3.1**

Note: single line ring indicates the MAX value; double line ring indicates the min value; bold font indicates the four optimum scenarios.

Table 3 shows the percentage variation of the design objectives with respect to the minimum value for the Pareto front scenarios. The first objective (operational carbon CO_2), varies between a minimum of 8,798 kg (approximately equal to 17.6 kg.m^{-2}.year) to a maximum of 9,374 kg (approximately equal to 18.7 kg.m^{-2}.year), with a percentage variation between min and MAX of about 6.5 % (approximately equal to 1.2 kg.m^{-2}.year); instead, the second design objective (discomfort hours), varies between a minimum of 1,160 hours to a maximum of 1,478 hours, with a percentage variation between min and MAX of about 27.4 %. Launching the optimization simulation with Design Builder, no priority was set up with respect to the two chosen design objectives. Nevertheless, the analysis of the variation between the minimum and the maximum value of both discomfort hours and operational carbon, the greatest percentage variation is recorded in correspondence with the discomfort hours parameter. Therefore, the priority to be applied on the chosen design objectives was defined after the analysis by checking the graphical results.

The numerical analysis of Table 3 shows four scenarios that better balance the percentage increase of the design objectives (yellow circle in Figure 4 and bold font in Table 3): the iterations 97, 188, 197 and 228. Table 4 shows the correspondent configurations.

Table 4. Iterations 97, 188, 197 and 228 characteristics

Iteration	Glazing type	Local Shading type	Window blind type	Wall insul. width (m)	Ceiling insul. Width (m)
97 (OPT-1)	G-3	LS-1	WB-3	WI-22	CI-24
188 (OPT-2)	G-5	LS-1	WB-3	WI-23	CI-24
197 (OPT-3)	G-3	LS-1	WB-3	WI-24	CI-22
228 (OPT-4)	G-5	LS-1	WB-2	WI-23	CI-23

All iterations consist of the most common envelope technological solutions in the sixteen optimization scenarios: G-3 and G-5 represent respectively the 25 % and 62.5 % of the total optimization scenarios; LS-1 the 31 %; WB-3 and WB-2 respectively the 62.5 % and the 25 %. The minimum value of operational CO_2 increases between the 3.7 % and 4.5 %; instead the minimum value of the discomfort hours amount increases between the 3.1 % and 3.6 %.

The solutions identified in the optimization process have been suddenly analyzed from the costs point of view, applying the Standard EN 15459:2017 [11], the revision of EN 15459:2007 [10].

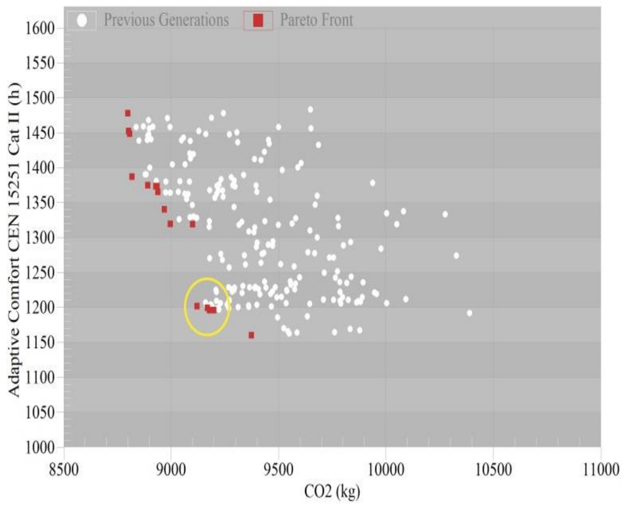

Figure 4. Pareto front - Optimization analysis results. Minimize CO_2 and Adaptive Comfort CEN 15251 cat II

Through the GC over a calculation period of 30 years, a comparison between the optimized solutions and the best cost-optimal energy scenarios identified in the previous research was possible, applying the new GC equation to all the scenarios, Eq.(1). In particular, the GC equation contains some new elements, as follows in Eq.1:

$$GC = CO_{INIT} + \sum_j [\sum_{i=1}^{TC} (CO_{a(i)}(j) * (1 + RAT_{xx(i)}(j)) * D\_f(i) + CO_{fin(TLS)}(j) - VAL_{fin(t_{TC})}\, t(j)] \quad (1)$$

where:

(1) CO_{INIT} , Initial Investment Costs, achieved from the price list for the execution of public works and maintenances of the City of Milan [26]. The missing price voices were based on market analysis, as requested by the Guidelines [23].

(2) $CO_{a(i)}(j)$, the Annual Cost for component or service j for year i. Annual Costs are the sum of all costs occurring during a specific year and involve energy consumption, operational, maintenance and replacement costs of each envelope and system component. To obtain the Energy Costs, the tariffs set by the Italian Regulatory Authority for Electricity Gas and Water (€ 0.2063 kWh-1 for electricity, € 0.7669 m^{-3} for natural gas) [27] have been applied. Maintenance and replacement costs of systems components are provided by the Annex D of the Standard EN 15459-1:2017 [11]. When data were not available, market analyses were considered. The lifespan of the envelope components is equal to the calculation period.

(3) $RAT_{xx(i)}(j)$, the price development for year i for component or service j; for the evolution of prices over the calculation period, a RAT equal to 1% for human operations, maintenance and products and equal to 2% for energy costs have been considered.

(4) $D\_f(i)$, the discount factor for year i, calculated from a discount rate equal to 1,63 %, calculated as the difference between the actualization rate, equal to 2,32 % [28] and the inflation rate equal to 0,69 % [29].

(5) $CO_{fin(TLS)}(j)$, the disposal cost for decommissioning, deconstruction and disposal in last year of lifecycle of component j; this cost is the real innovation of the update Standard. Disposal costs are provided in Annex D of Standard EN 15459-1:2017 [11] as a percentage of the initial cost for component.

(6) $VAL_{fin(t_{TC})}$, is the residual value for component j at the end of the calculation period.

As in the previous research, the CO_2 emissions related costs have not been considered since the evaluation is carried out at financial level and not at a macroeconomic one.

Then the discounted payback period has been used for a complete comparison of the optimized solutions with the previous ones identified with the cost-optimal method. The discounted payback period equation is contained in the Standard EN 15459-1: 2017 [11]:

$$\sum_{t=1}^{TBP} CF_t \left(\frac{1}{1+RAT_{disc}}\right)^t - CO_{INIT} + CO_{INITRef} = 0 \quad (2)$$

where:

(1) CF_t is the difference of annual costs (cash flow difference) between the optional case and the reference case at year t;

(2) TPB is the last year of PB;

(3) RAT_{disc} is the discount rate;

(4) CO_{INIT} is the initial investment cost;

(5) $CO_{INITref}$ is the initial investment cost for reference case.

The results of the pay-back period calculation are shown in Table 5; the payback is highly reduced by the application of National Incentives that see a consistent cut of the initial investment costs.

In the previous research [9], the Cost Optimal methodology [24] was applied to an existing social housing and research was focused on finding the best configuration in terms of GC and Ep. The research found a range of three best ES in n ZEB class: ES12, ES17 and ES18. The district heating proves to be the best plant solution for the three scenarios; the difference was represented by a medium or high insulation level and by more or less PV panels surface. In the first step, only economic and energy target were analyzed, while environmental and comfort analysis were excluded. Furthermore, the EN 15459-1:2007 [10] has been update, therefore in the current study the GC and the PB for the three best configurations have been re-calculated in accordance with the EN 15459-1:2017 [11] and compared with the output of the optimization analysis. The output is described in Table 5.

Among the four optimized solutions (Table 4), OPT-2 and OPT-4 have been excluded from the assessment after an economic evaluation revealing that the four solutions have an insignificant variation, since OPT-1 and OPT-3 have a better technical feasibility.

The case study was social housing and the budget didn't permit to invest in a conditioning system. So the optimization analysis was focus to find a configuration to reduce the CO_2 emission but in particular to minimize the summer discomfort hours (in accordance to EN 15251, cat.II). An important role was played by the shading systems and by the type of glass. Table 5 shows that the more investment for the solar control (OPT-1 and OPT-3) doesn't create a relevant difference with the ES 12, ES17 and ES18 in terms of GC and PB. In this case, it is possible to confirm that the extra-costs for co-benefits can be widely justified.

Table 5. Comparison of GC and PB of options

Variant Package	Initial Investment Cost (€)	Annual Running Costs (€)			Residual Value (€)	Disposal Costs (€)	GC (€)	GC (€/m²)	PB (y)
		Maintenance	Replacement	Energy cost by fuel					
ES12	221,774.14	4,121.62	86,014.21	70,555.22	40,702.36	7,497.41	328,726.50	232.93	8-9
ES17	242,456.91	4,121.62	68,892.63	70,965.99	34,271.28	5,802.20	309,323.10	219.18	9-10
ES18	234,749.76	4,121.62	86,014.21	65,750.27	40,702.36	7,497.41	336,133.36	238.18	9-10
OPT-1	245,193.67	13,250.73	91,719.44	63,326.05	44,780.25	7,782.67	355,194.67	251.68	9-10
OPT-3	245,599.87	13,250.73	91,719.44	63,107.18	44,780.25	7,782.67	355,636.69	252.00	9-10

5. CONCLUSIONS

In a holistic approach, optimization analysis permits to take into account at the same time energy and economic aspects with environmental and comfort ones. In this paper, the optimization analysis reveals four best scenarios and, after a numerical and the GC analysis, two similar configuration were selected.

Often co-benefits are not adequately perceived by users benefitting or by the investors taking the renovation, not even they are supported by the specialist technical adviser of the investment decisions [6]. In this case study it is evident that the pay-back period doesn't vary when the technical solutions for summer comfort improvement are applied. This result is very important because justifies a small extra-cost compared to the total initial investment, giving the possibility to apply the best retrofit solutions not only from the economic and energy point of view. Nevertheless, for cases involving a higher complexity level that require the assessment of more objectives, a MOO analysis can be a valid method to be added to an optimization study.

The MOO analysis needs to be integrated with a Multi-Criteria Decision Analysis: MCDA permits to find the best energy efficiency measures, allowing to simultaneously evaluate different aspect of the building behavior and working as a support system to compare different technical solution and to detect the best ones able to achieve a specific or multiple goals.

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NOMENCLATURE

CO_2	Carbon dioxide, kg
GHG	Greenhouse Gas Emissions
MOO	Multi-Objective Optimization
ZEB	Zero Energy Building
IEA	International Energy Agency
NSGA2	Non Sorting Genetic Algorithm II
GC	Global Cost, € or €/m^2
Ep	Primary energy indicator for global not renewable energy, kWh.m^{-2}
PB	Payback Period
S	Width, m
U	Thermal transmittance, W. m^{-2}. K^{-1}
g	Dimensionless solar factor
TL	Dimensionless light transmission
WI-10 to WI-24	Wall Insulation variables
CI-12 to CI-24	Ceilings Insulation variables
G-1 to G-5	Glass variables
LS-1 to LS-6	Local shading variables
WB-1 to WB-5	Window blinds variables
OPT-1 to OPT-4	Optimal scenarios selected
CO_{INIT}	Initial Investment Costs
$CO_{a(i)}(j)$	Annual Cost for component or service j for year i.
$RAT_{xx(i)}$ (j)	Price development for year i for component or service j
D_f (i)	Discount factor for year i
CO $_{fin(TLS)}$ (j)	Disposal cost for decommissioning, deconstruction and disposal in last year of lifecycle of component j
VAL $_{fin(tTC)}$	Residual value for component j at the end of the calculation period
CFt	Difference of annual costs (cash flow difference) between the optional case and the reference case at year t
TPB	Last year of PB
RAT_{disc}	Discount rate
$CO_{INITref}$	Initial investment cost for reference case
ES	Energy Scenario
MCDA	Multi-Criteria Decision Analysis