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The Influence of Technology Performance Durability in the Cost-Optimal Analysis of a ZEB

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Abstract. The high number of existing buildings needing refurbishment actions justifies the need of a methodology that considers its service life after the refurbishment process. Cost-effectiveness assessment of refurbishment scenarios in building design is a crucial phase in the decision-making process towards a ZEB realization. Energy renovations involve an important investment, whose amount increases considerably when a ZEB target is fixed. When cost-optimal methodology is applied to different refurbishment scenarios, the costs evaluated take into consideration not only the initial investment cost, but also the running costs over the years and the payback time of the adopted solutions. Nevertheless, technologies hypothesized in the scenarios undergo a process of performance decay taking place since the first year of buildings' operations. The thin balance between needs and energy supply of a ZEB may be broken by deteriorating the energy performance of the whole building. Consequently, the running costs can increase significantly over the years and also the payback time, calculated over the annual costs of the building. The goal of this paper is to apply a cost-optimal assessment on a reference building, comparing the results of simulations with durability approach and those that do not consider the performance decay.

1. Introduction

Buildings are responsible for approximately 40% of energy consumption and 36% of CO_2 emissions in the EU. Currently, about 35% of the EU's buildings are over 50 years old and almost 75% of the building stock is energy inefficient, while only 0.4-1.2% (depending on the country) of the building stock is renovated each year. Therefore, more renovation of existing buildings has the potential to lead to significant energy savings – potentially reducing the EU's total energy consumption by 5–6% and lowering CO_2 emissions by about 5% [1]. The EPBD recast [2] and the following directive (EU) 2018/244 [3] do not introduce only the concept of nZEB and ZEB respectively, but also that one of cost optimality: the renovation of the building stock shall ensure the minimum energy performance requirements achieving a cost optimal level. The Cost-Optimal methodology is provided by the European Regulation n.244/2012 [4] and describes a method to find the refurbishment solutions to guarantee the best energy performance with the lowest cost during the estimated economic lifecycle. This methodology carries out a macroeconomic analysis useful for PAs but it is also possible to achieve a financial analysis related to a specific case study.

In order to achieve the performance required by a ZEB [5] and [6], advanced existing and innovative technologies with best performance are often used [7], [8], [9] and [10], while its performance decay has rarely been considered [11]. The Standard EN 15459-2 describes the calculation of the Global Cost

(GC) and specifies that operating conditions have to be considered constant during the duration of the calculation period [12].

Building envelope and system plants performance decrease over time due to natural degradation, environmental conditions and poor maintenance [13] and [14]. This "performance degradation" could be the cause of higher life cycle costs as compared to that expected during the design phase, since its effects are generally not analysed, neither by energy calculation standard nor by conventional simulation models [15] and [16] or existing optimization concepts [13]. This paper presents the Cost Optimal method applied to a case study considering the degradation rate and not in order to compare its influence on analyses results.

2. Method

After the definition of the Energy Refurbishment Solution (ERS) and their combination in Energy Scenario (ES), the paper presents the application of the cost-optimal methodology according to the European Regulation n.244/2012 [4] calculating the GC, as described in EN 15459-1 and 2 [17], [12]. The results are compared calculating the GC and the performance decay of the chosen envelope, system and RES solutions, as described in **Figure 1**.

2.1. Case study

The test-laboratory, located in an industrial area of on the southwest outskirts of Milan (45°23'N, 9°15'E, Italian climate zone "E", 2,404 Heating Degree Days), simulates an office building reusing an existing single-storey structure with a concrete-based flat roof and brick walls. The external dimensions are of about 7 x 8 x 4 m (length x width x height), with two windows on South-East facade and 1 window on North-West façade (1.1 x 1.6 m), (Figure 2). The laboratory is internally divided into three spaces: two are used for offices (A1 and A2) and the small one (A3) is used as technical room for plants. The external envelope construction systems are composed by different layers and the actual thermal performances are listed in **Table 1**. The windows have aluminium frame without thermal break and single glazing.

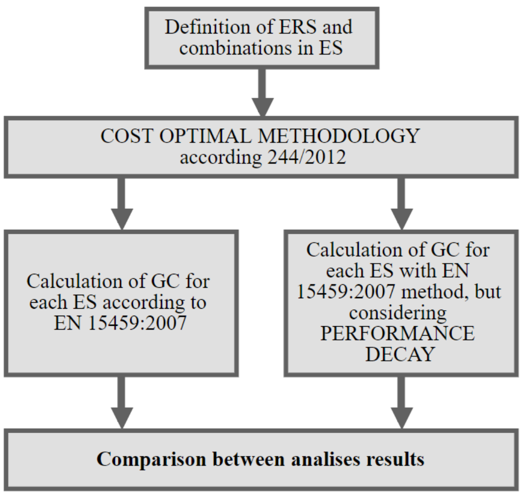

Figure 1. Methodological approach scheme

Table 1. Existing envelope thermal performances

	s	U	R
M1	0.25	0.578	1.729
M2	0.14	2.17	0.461
M4	0.24	1.611	0.621
Roof	0.30	1.63	0.614
Ground floor	0.37	0.85	1.174
Windows	U = 5.8	G = 0.82	LT = 0.70

The existing plant consists of a methane boiler generator with fan coils as terminals in each room. The system is regulated by a single thermostat placed in A1 space. The cooling is supplied by direct expansion mono-split electric air conditioners.

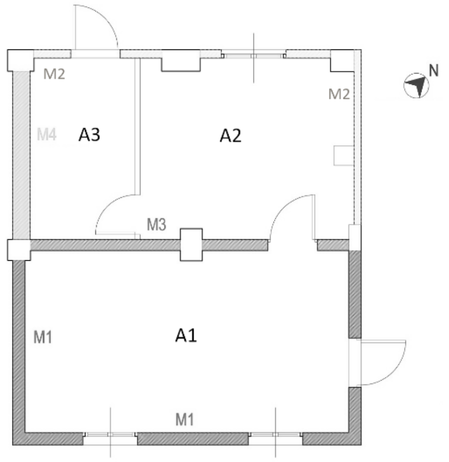

Figure 2. Plan of the laboratory

Figure 3. External view of the laboratory before the renovation

2.2. Energy refurbishment scenario

According to the Guidelines n.244/2012 [4], the more packages and variations measures included in the assessed scenario are use, the more accurate the calculated optimum of the achievable performance will be, with a minimum of packages/variations set equal to 10 [18]. In this case study the ERS are divided into envelope, plant and RES and then combined to obtain 12 ES to be assessed.

For the envelope two insulation systems are analysed: EPS with thermal conductivity λ_{init} = 0.036 W/mK (ERS1) and VIP with λ_{init} = 0.004 W/mK (ERS2). The width (s) of EPS has been calculated to reach the thermal transmittance (U) limit required by the Italian National Decree 26/06/2015 [19], while the VIP has a width of 2 cm. The new envelope performances are listed in Table 2. Both in ERS1 and ERS2 there is a triple glazing low-e filled with argon (44.1/12 argon/66.2/12 argon/66.2) and an aluminium frame with thermal break to achieve the performances listed in Table 2:

Table 2. Energy Refurbishment solution for the building envelope

	ERS 1		ERS 2		limits
	U	s	U	s	U
M1	0.26	0.08	0.15	0.02	0.26
M2	0.26	0.12	0.18	0.02	0.26
M4	0.26	0.12	0.18	0.02	0.26
Roof	0.22	0.14	0.18	0.02	0.22
Ground floor	0.26	0.10	0.16	0.02	0.26
windows	U_w = 1.40	g = 0.35	LT = 0.53		1.40

The plants configurations are determined choosing mostly or totally renewable generators with the double aim to reach the nZEB/ZEB efficiency class and to respect the renewable percentage required by the Italian Legislative Decree n.28/2011 [20]: if renovations are important, the energy produced from plants powered by renewables sources must ensure the covering of 50% of the consumption planned for heating, cooling and hot water.

The adopted solutions for plants and RES are:

- ERS 3: geothermal heat pump (GSHP) with heating and cooling radiant floor;
- ERS 4: condensing boiler and chiller with fan coil;
- ERS5: 1 kW PV panels and solar panels
- ERS6: 2 kW PV panels and solar panels
- ERS7: 5 kW PV panels and solar panels

The combination of envelope, plants and RES energy refurbishment solution brings to the formulation of 12 ES to be assessed, as illustrated in Table 3.

Table 3. The ES and the corresponding ERS considered

ES	Envelope	Plants	Renewable
1	ERS 1	ERS3	ERS 5
2	ERS 1	ERS3	ERS 6
3	ERS 1	ERS3	ERS 7
4	ERS 1	ERS4	ERS 5
5	ERS 1	ERS4	ERS 6
6	ERS 1	ERS4	ERS 7
7	ERS 2	ERS3	ERS 5
8	ERS 2	ERS3	ERS 6
9	ERS 2	ERS3	ERS 7
10	ERS 2	ERS4	ERS 5
11	ERS 2	ERS4	ERS 6
12	ERS 2	ERS4	ERS 7

2.3. Degradation rate

Plants and envelope performances are affected by a degradation mainly due to effects of ageing, environmental conditions and bad maintenance. Since specific data are still missing in standard and decrees, in this paper scientific literature analyses are considered. The ageing of gas-filled glazing double sealing, VIP, GSHP and PV panels are considered in [11], while EPS, boiler and chiller degradation rate are analysed in [14]. In the last research, the authors provide a range of variation of each ageing parameter over 50 years for low degradation and high degradation rate.

The degradation rates are represented as a mean value and listed in Table 4.

Table 4. Degradation rate of efficiency of technology

Years	Gas-filled glazing double sealing	EPS	VIP	GSHP	boiler	Chiller	PV
1	- 1 %	- 1.85 %	- 2 %	- 2 %	- 1 %	- 1.7 %	- 3 %
5	- 5 %	- 9 %	- 10 %	- 5 %	- 4 %	- 8.5 %	- 5 %
10	- 10 %	- 18.5 %	- 20 %	- 8 %	- 8 %	- 17 %	- 10 %
25	- 25 %	- 46 %	- 50 %	- 14 %	- 20 %	- 42.5 %	- 20 %

2.4. Energy and economic calculation

For the calculation of the energy needs, the monthly method is employed through a commercial software approved by the National Thermo-technical Committee, CTI [21]; the software implements the Standard method of UNI/TS 11300 [22], the Italian standard transposing the EN ISO 13790:2008 [23].

When the degradation rate is considered (Table 4), the energy needs are updated every five years changing the performances of the envelope and the plants.

The GC of each ES is calculated applying the Standard EN 15459:2017 [17] as described in the following equation:

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

where:

- CO_{INIT} , Initial Investment Costs, achieved from the price list for the execution of public works and maintenances of the City of Milan [24]. The missing price voices are based on market analysis, as required by the Guidelines [4].
- $CO_{a(i)}(j)$, the Annual Cost for component or service j for year i, calculated over a period of 30 years, in accordance with the guidelines for retrofit analysis [4]. 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 Standard EN 15459-2 are applied [12]. Maintenance and replacement costs of systems components are provided by the Annex D of the Standard EN 15459-1:2017 [17]. When data are not available, market analyses are considered.
- $RAT_{xx(i)}(j)$, 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 are considered.
- $D\_f(i)$, the discount factor for year i, calculated from a discount rate equal to 2.12% calculated as the difference between the actualization rate, equal to 3.16% and the inflation rate equal to 1.04 % [25].
- $CO_{fin(TLS)}(j)$, the disposal cost for decommissioning, deconstruction and disposal in last year of lifecycle of component j; disposal costs are provided in Annex D of Standard EN 15459-1:2017 [17] as a percentage of the initial cost for component.
- $VAL_{fin(t_{TC})}$, is the residual value for component j at the end of the calculation period.

2.5. Results

In Figure 4 the Cost Optimal curves are compared with and without including the performance decay. Some considerations can be highlighted:

- ES3 and ES9 represent, on the one hand, the achievement of ZEB requirements and on the other the most expensive renovations;
- with ERS 3 (GSHP) primary energy requirements of less than 15 kWh.m^{-2}.y are reached while with the ERS 4 (boiler, chiller and fan coils) EP values are between 25 and 55 kWh.m^{-2}.y;
- with the ESR 3 system, it is evident that ES2 is the best solution in terms of GC and EP. With ERS 4 system, both ES11 and ES 5 can be considered the cost-optimal solutions.
- For higher primary energy requirements, the effect of the performance decay becomes more incisive (Figure 4 and Figure 5). When the EP is less than 15 kWh.m^{-2}.y, the ΔEP (difference between EP after 25 years and initial EP) is less than 2 kWh.m^{-2}.y. Otherwise when the EP increases, the ΔEP reaches 10 kWh.m^{-2}.y.
- The high thermal insulation provided by the VIP causes a slight increase in the energy requirements for cooling, which is more evident in the best performance solutions (ES7, 8 and 9). Instead with the ERS 4 system, the overall performance of solutions with VIP (ES10, 11 and 12) remains better after 25 years than that initial one with EPS insulation (ES 4, 5 and 6).

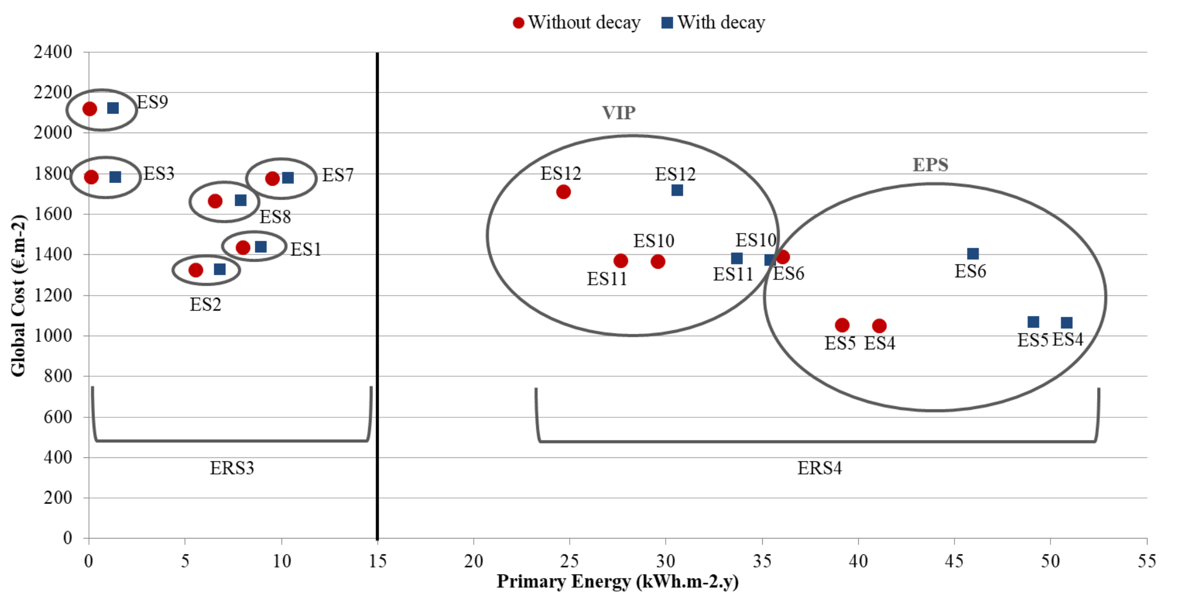

Figure 4. Cost-Optimal solutions with (blue colour) and without (red colour) performance decay

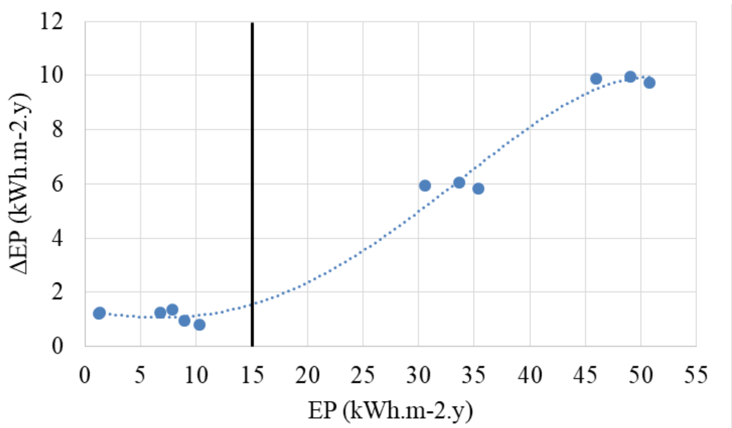

Figure 5. Primary energy increasing with performance decay

3. Conclusion

When the primary energy requirements are less than 15 KWh.m^{-2}.y, the Cost-Optimal analysis is not influenced by the variation of the envelope and plant components performance.

In this case study the performance decay influences only the EP value because the Energy Cost is less than 10% of the Initial Investment Cost. In the ES9 which represents the ZEB solution, Energy Cost is 1%. The Figure 6 shows the increase of Energy Cost due to the EP getting worse over the calculation period and the reduction of Initial Investment Cost. It also highlights the different impact of them.

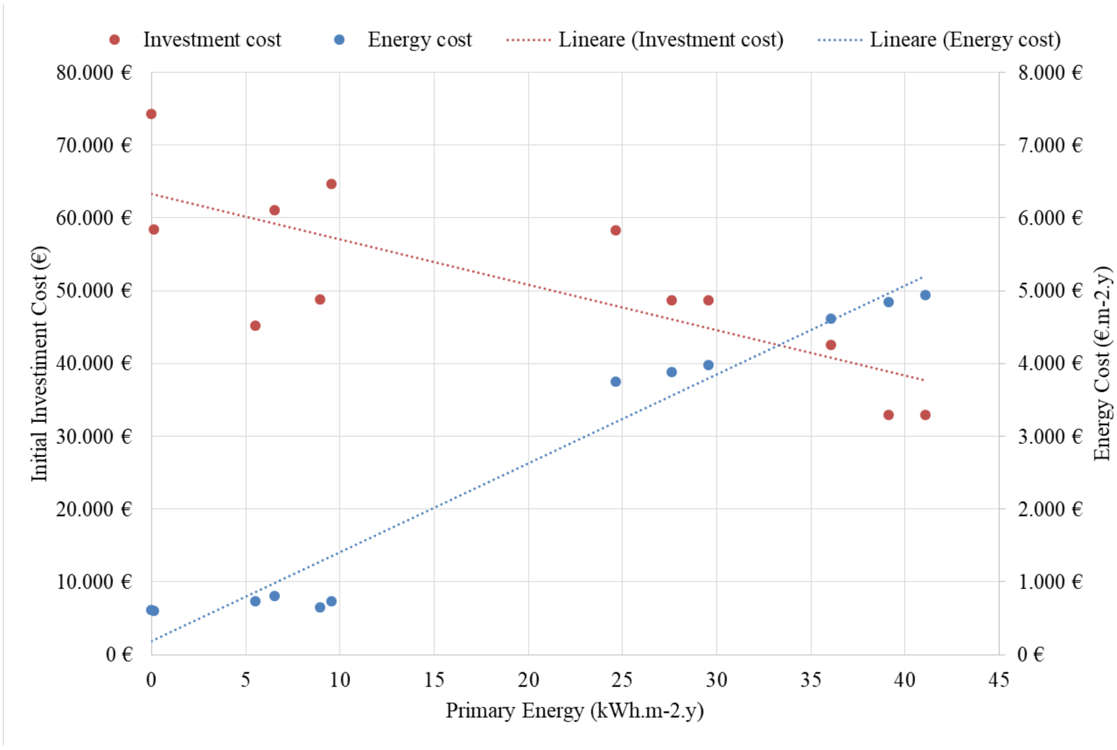

Figure 6. Comparison between Costs (Initial Investment and Energy) and Primary Energy

The cost-optimal methodology (Standard EN 15459-2) shall therefore consider and implement the decay of performance in its formulas, being the calculation based on a period never shorter than 30 years. The principle of cost-optimality is in fact based on a duration period, considering costs like maintenance, disposal and energy consumption. In this context, it appears evident the convenience of a higher investment cost aimed at keeping lower the Primary Energy (<15 $KWh.m^{-2}.y$) over the years and at reducing the weight of performance decay.

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