D'Orazio M., Di Giuseppe E. *"Uncertainty impact on decisions related to historical buildings energy retrofit"*.

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ABSTRACT

Decisions concerning energy retrofit of historical buildings should be based on a complex set of parameters, ranging from not-tangible to tangible values, such as the historical and the cultural value, the expected costs and benefits, the environmental impacts. The tangible values, such as the monetary costs and benefits, are often prioritized considering their measurability, however neglecting that they are frequently affected by important uncertainties (related e.g. to the evolution of the macro-economic scenario, to the building components maintenance and replacement needs, etc.). This fact can lead to improper design choices and consequently to the risk of losing part of the building tangible or not-tangible value. For this reason, it is necessary to improve decision-making processes and tools, also considering uncertainty and sensitivity analysis as part of the design process related to the energy retrofit of historical buildings. In this paper we show the impact of different assumptions regarding future possible macro-economic scenarios on the monetary benefits of a historic building renovation intervention. A "probabilistic" Life Cycle Costing tool, developed through the software environment for statistical computing "R", has been used to evaluate the parameters mostly influencing the global costs of the typical energy retrofit measures applied to a building case-study. Results demonstrate how the uncertainties related to the economic parameters are the most influencing the output variance. The uncertainties related to the building periodic maintenance and the energy costs are also prevailing on those related to the initial investment costs.

1. INTRODUCTION

Considering that in today's Europe 30% of all buildings are historic buildings that are expected to last for decades, there is great potential for energy savings and consequently exploitable emission reductions in historic buildings. More attention should then be given to the renovation strategies and technologies aiming at existing buildings in different climates and conditions. This however implies facing the inherent risks and constraints relating to the life cycle of the building components.

Indeed, the circular economy paradigm applied to the construction sector requires a better understanding of the phases following the "construction" or "refurbishment" phase. Environmental and economic impacts related to the "use" and "dismission" phases are in fact normally more relevant than impacts and costs related to the construction or refurbishment phase, considering the long life of a building, especially of a historic building.

However, while environmental and economic impacts of the construction or refurbishment phase are normally well known, as they are "present" impacts or costs hence characterized by low uncertainty, impacts related to the building use and dismission are quite uncertain, as they are "future" impacts related to unknow scenarios. For instance, future economic impacts related to the building running costs, as the energy costs are strongly related to the future macro-economic scenario that affect the assessment parameters as the interest and inflation rates, or the prices development rates.

Hence to promote a real attention to the building whole life cycle (construction, use, dismission) there is the necessity of a better comprehension of the uncertainties characterizing use and dismission phases. Misleads on the quantification of impacts related to the future phases could promote renovation measures not justifiable from a life-cycle point of view.

Uncertainty (UA) and sensitivity analysis (SA) procedures have then to become part of the building design process related to the retrofit of historical buildings, to improve the reliability of decision making. To date in Life Cycle Assessment (LCA) and Life Cycle Costing (LCC), only little has been done in terms of uncertainty and sensitivity analysis and international standards are not exhaustive regarding these aspects. Only few authors [1]–[3] promoted the introduction of uncertainty and sensitivity analysis procedures to evaluate impacts, cost and benefits related to buildings refurbishment processes and to understand the opportunity of specific fiscal policies [4]–[6] considering alternative scenarios [7].

A "probabilistic" approach to building LCC, as that presented in this paper, considerably improves the reliability of LCC-based decision making and allows for overcoming the evident limitations of traditional deterministic LCC approaches. It can be effectively applied to offer decision support during the building renovation phase, providing possible ranges of the economic impacts of renovation measures under alternative scenarios. Furthermore, it offers an idea of the significance of input parameters' uncertainties and their impacts on the results, through the sensitivity analysis.

This paper presents the Monte-Carlo based LCC methodology developed by the authors (section 2) and the application to an historical building case-study (described in section 3). Results are presented and discussed in section 4.

2. CALCULATION METHODOLOGY

A probabilistic LCC web tool to perform cost-benefit analysis of energy retrofit interventions has been developed using "R", a software environment for statistical computing, based on a methodology that couples the calculation method described in standard EN 15459-2017 [8] with a Monte-Carlo based approach in order to build the output probability distribution and to assess global uncertainty and sensitivity [9].

The method considers the Probability Density Functions (PDF) of the input parameters of the global costs and payback period equations of EN 15459, such as the initial and running costs of the renovation measures (investments, replacements, related energy needs), their service life, and the macro-economic parameters related to possible alternative evolutions of macro-economic scenarios.

The Global Cost (GC_{cp}) at the end of the calculation period (cp) referred to the starting year is calculated based on the method described in standard EN 15459 [8] through the following Eq. 1:

$$GC_{cp} = \sum_{j=1}^{N} \left\{ CI_j + \sum_{t=1}^{CP} \left[\left(CM_{j,t} * R_t^{disc} * R_t^L \right) + \left(CE_{j,t} * R_t^{disc} * R_t^E \right) \right] + CR_{j,t_j} - Val_{j,cp} \right\}$$

Eq. 1

Where:

t is the number of the year;

j is the renovation measure;

cp is the calculation period;

CI_j is the initial investment cost of the renovation measure j;

$CM_{j,t}$ is the annual maintenance cost of the renovation measure j;

$CE_{j,t}$ is the annual energy cost due to the renovation measure j ;

R_t^{disc} is the discount rate;

R_t^L is the price development rate for human operation (labour cost);

R_t^E is the price development rate for energy;

CR_{j,t_j} is the replacement cost;

$Val_{j,cp}$ is the residual value of the renovation measure at the end of the calculation period.

In the methodology developed, the calculation of GC is "dynamic", i.e. annual variations of the discount rate as well as annual variations of the price development rates of the annual costs (i.e. energy costs, periodic or replacement costs, maintenance costs) are considered.
The discount rate R_T^{disc} at any generic time period T is a function of the inflation rate, π_t, and the nominal interest rate, i_t^N.
R_T^L and R_T^E are the price development rates that are applied to all cost components of the LCC equation (i.e. energy costs, periodic or replacement costs, maintenance costs), that depend on the escalation factor of the prices for human operation i.e. the growth rate of GDP (Gross Domestic Product) and the escalation factor of the prices for energy, i.e., the growth rate of crude oil price.
A "regular growth" (RG) macro-economic scenario has been characterised and the related parameters, as the nominal interest rate, the inflation rate and the growth rate of GDP expressed in real terms, have been forecasted from historical data using a Vector autoregression (VAR) methodology. The RG scenario represents the dynamics of an economic system with a balanced growth path, i.e., with moderate growth in inflation and in GDP and moderate nominal interest rate. This scenario is characterized by a real GDP growth around 2.5% (standard deviation -sd- of about 1.6%) and an inflation rate around 2.2% (sd 0.9%). Interest rate, in nominal terms, is around 5% (sd 1.5%).
The discounted payback period (PB) is the time when the difference between the initial investment cost for the renovation and reference cases are balanced with the cumulative discounted annual costs difference in each individual year. The payback period can then be calculated as the number of years, S, required to the cumulative energy savings to equalize the initial investment costs and its subsequent operating costs (maintenance and replacement costs).
The LCC assessment requires input data on operational energy use before and after the renovation measure in order to take into account the "use phase" (energy costs) and determine the costs savings. The energy cost (CE) is an annual cost for the delivered energy for heating, including national taxes. It is obtained multiplying the annual energy consumption by the tariff for the energy carrier considered. Since the LCC is performed considering only the envelope intervention, the delivered energy concerned is the heating energy that depends on the energy need expressed by the heat transmission loss through the wall (Qh) and the building global efficiency for heating (ETAh).
For the uncertainty propagation, Monte Carlo methods are chosen to propagate the LCC parameter uncertainties into a distribution of the output variable (global costs [€] and payback period [years]). Sobol's sequences are used as quasi-random sampling technique, in order to generate samples as uniformly as possible and effectively perform the sensitivity analysis through variance based decomposition (Sobol' method) techniques, to evaluate the impact of each input parameter variance on global cost variance [10], [11]. Through these methods, it is possible to obtain two sets of indices for each stochastic input: the "first order" and the "total order" indices. The first-order sensitivity index represents the main contribution of each input factor to the variance of the output. The total order index measures the contribution to the output variance due to each input, including the variance caused by its interactions with any other input variables. The higher the value of the sensitivity indices, the most influential are the related parameters of the model.

3. DESCRIPTION OF THE CASE STUDY

Figure 1. Building case-study. View of the facades(a); plans (b)

The calculation methodology has been applied to a specific case study, a single-family house of beginning XX Century, representing a large part of the existing Italian residential historical stock (fig.1). The building has a base area of 96 m^2 and 3 floors (ground floor, first floor plus an attic), for a total volume of 690 m^3. External, original walls are in plastered brick masonry with variable thicknesses, from 29 cm (U=1.76 W/m²K) to 16 cm (U= 2.58 W/m²K). Original floors and roof consisted on wooden slabs without insulation, with respectively floor tiles (U=1.29 W/m²K-first floor slab) or clay tiles (U=1.68 W/m²K). Furthermore, the building included single glazing windows with timber frames and a combined heating and domestic hot water equipment consisting on a traditional gas non-condensing boiler. Energy consumption of this building typology is largely due to the poor performance of the exterior wall and a typical energy retrofit measure is the internal insulation of the exterior wall to preserve the architectonic features of the façade.

For the external wall, three alternative internal insulation solutions have been conceived, in order to compare their energy and economic performance: EPS coupled with a plasterboard panel directly fixed to the wall through a specific mortar; Cork finished with a specific mortar as surface rendering and directly fixed to the wall through a mortar; Rockwool coupled with a plasterboard panel fixed to the wall through a metallic frame. The internal insulations allow reaching almost the same U-value for the wall based on the actual Italian law requirements. Italian Ministerial Decree 26/06/2015 imposes U ≤ 0.28 W/m²K for "second level renovation" interventions in the Italian climatic zone "E" [12]. In accordance with D.M. 26/06/2015 this value has been increased by 30% since we are using internal insulation solutions: U ≤ 0.364 W/m²K). The U-values of the insulation systems are then: 0.33 W/m²K for the insulation system B and 0.34 W/m²K for the insulation systems A and C. The slight differences depend on the commercial insulation thicknesses available in the market.

Concerning the heating equipment, three different solutions were taken into account, characterised by different energy sources (gas, electricity and oil) among the most widespread in Italy.

The calculation of the Global Costs was performed considering four different calculation periods, 30-40-50-60 years under.

The combination of all the envelope and equipment renovation measures and the calculation periods gave rise to 36 simulation cases, reported in Table 1.

Table1. Simulation Cases

Case	**Cp**	**Internal Insulation**	**Energy Source**	**Case**	**Cp**	**Internal Insulation**	**Source**	**Case**	**Cp**	**Internal Insulation**	**Energy Source**
1	30	EPS-plasterboard (C_S_Test1)	Gas	*13*	30	EPS-plasterboard (C_S_Test1)	Electricity	*25*	30	EPS-plasterboard (C_S_Test1)	Oil
2	40			*14*	40			*26*	40		
3	50			*15*	50			*27*	50		
4	60			*16*	60			*28*	60		
5	30	Cork-rendering (C_S_Test2)		*17*	30	Cork-rendering (C_S_Test2)		*29*	30	Cork-rendering (C_S_Test2)	
6	40			*18*	40			*30*	40		
7	50			*19*	50			*31*	50		
8	60			*20*	60			*32*	60		
9	30	Rockwool-plasterboard (C_S_Test3)		*21*	30	Rockwool-plasterboard (C_S_Test3)		*33*	30	Rockwool-plasterboard (C_S_Test3)	
10	40			*22*	40			*34*	40		
11	50			*23*	50			*35*	50		
12	60			*24*	60			*36*	60		

Table2. Input parameters PDFs. Qhpre=energy need for heating before renovation; Qhpost=energy need for heating after renovation; EnT= Energy Tariff; ETAh = overall equipment efficiency for heating. Par 1 and Par2 characterise the distributions: they are respectively the mean and standard deviation (sd) for the normal distribution and the minimum and maximum values for the uniform distribution.

	Parameter	**Distribution type**	**Par1**	**Par2**	**Unit**
Energy consumption PDFs	Qh pre	Normal	100.63	6.57	kWh/m2
	Qh post	Normal	14.12	2.35	kWh/m2
Cost PDFs	CI-EPS	Normal	40.42	5.59	€/m2
	CM-EPS	Normal	0.88	0.12	€/m2
	SL-EPS	Normal	30	2.98	Years
	CI-CORK	Normal	79.01	10.91	€/m2
	CM-CORK	Normal	0.88	0.12	€/m2
	SL-CORK	Normal	30	2.98	Years
	CI -ROCKWOOL	Normal	52.33	7.12	€/m2
	CM-ROCKWOOL	Normal	0.88	0.12	€/m2
	SL-ROCKWOOL	Normal	30	2.98	Years
Energy Source (Gas) PDFs	EnT	Uniform	0.065	0.085	€/kWh
	ETAh	Uniform	0.6	1	-
Energy Source (Electricity) PDFs	EnT	Uniform	0.158	0.214	€/kWh
	ETAh	Uniform	2.5	4	-
Energy Source (Oil) PDFs	EnT	Uniform	0.115	0.135	€/kWh
	ETAh	Uniform	0.4	0.8	-

The heat transmission losses through the wall were calculated using a probabilistic annual heating degree-days (HDD) method. PDFs of temperatures data were calculated from Eurostat weather database for Italy for years from 2000 to 2016, considering their variability during time and space (the Italian region Emilia-Romagna, climatic zone “E”).

PDFs of Investment costs (CI) and maintenance costs (CM) were obtained from market data.

The estimated Service Life of the building components was calculated based on the probabilistic factorial method of standard ISO 15686-8 [13].

Considering the energy source scenario, a uniform distribution was assigned to the heating equipment efficiency based on authors' judgment.

The PDFs for the energy tariffs of gas and electricity in the Italian context were established to be uniform distributions by considering, as mean value, the energy tariff for the energy source in the regulated market, and as variability source, the energy tariff variability for the energy source in the free market. The tariffs of the oil, on the other hand, have been evaluated through the elaborations of the Oil industry Union (that represents the oil companies working in the Italian market), based on monthly oil price observations by the Ministry of Economic Development.

Table 2 reports the details on the input parameters PDFs.

5632 simulation runs were performed, based on preliminary investigations on the accuracy of this sample size, and finally the probability distributions of the resulting global costs and payback periods were obtained.

4. RESULTS

4.1. Sensitivity analysis

Figure 2 shows the boxplots of the first and total order indices for the LCC inputs in all the simulated cases, in the two extreme calculation periods assessed: 30 years (top) and 60 years (bottom). From the graphs, it is evident how the input ranking varies across the two calculation periods. The width of the box plots depends on the influence of the different insulation systems and energy sources considered.

For both calculation periods, looking at the total order indices, the most influential parameter is the Interest Rate, responsible averagely for about 50% of the output variance in the 30-years period and 70% in the 60-years period. Furthermore, in the first case, the other influencing parameters are: GDP, Qhpost and ETAh, underlining the impact of the uncertainty related to the energy costs considering a shorter assessment period. Otherwise in the second case, GDP is basically responsible for the rest of the variance. This means that in a long-term perspective the uncertainty of the macroeconomic scenario is the most influential factor in LCC analysis.

From these results, it also arises that some parameters uncertainties are no influencing in both calculation periods: the energy tariff and the inflation rate, while insulations costs and service life have a certain impact in the shorter period.

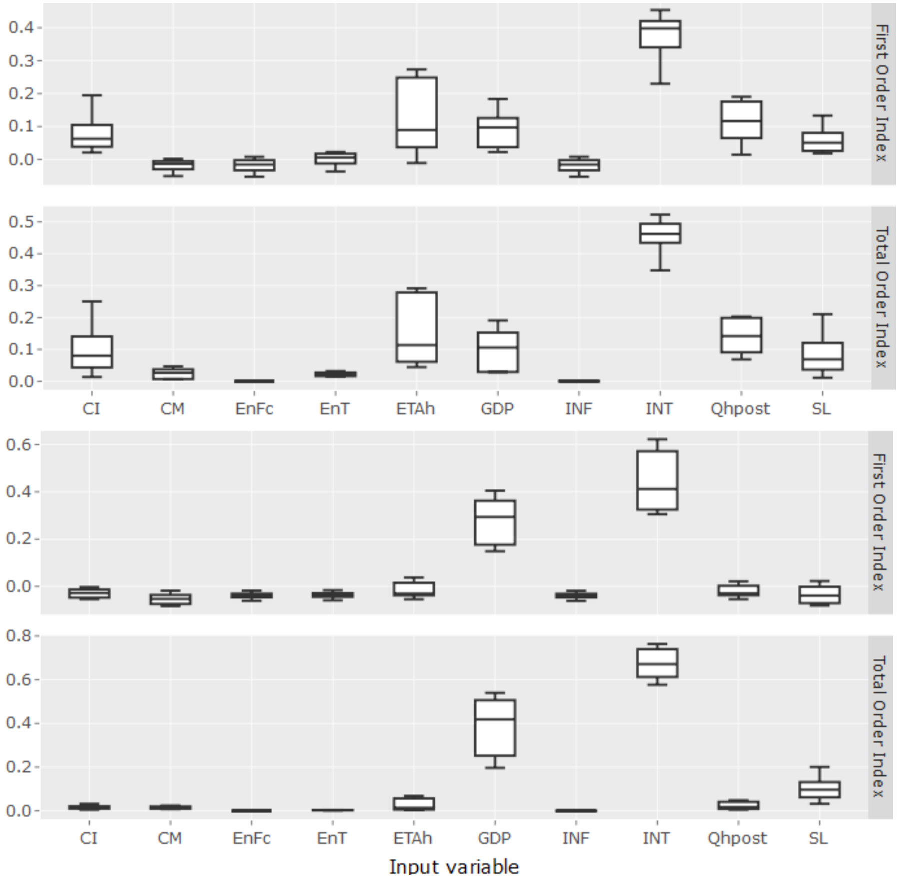

Figure 2. Aggregated sensitivity analysis results for a calculation period of 30 years (top) and 60 years (bottom).

4.2. Global costs and Payback Periods

Figure 3 and Figure 4 show, in a “mean-sd” space, the expected Global Costs and Payback Periods mean and standard deviation values for each alternative insulation system case (C_S_Test, in the rows) in the different energy scenarios (different colours). For the GCthe different calculation periods are also reported (columns).

What in general emerges in all scenarios is that insulation solution 1 (EPS) is the one able to guarantee minor Global Costs, followed by Solution 3 (Rockwool) and 2 (cork). For instance, under the gas energy scenario and a 30-years calculation period, the median values of the GC vary from about 121 €/m² for the insulation system 1 (EPS) to 159 €/m² for the insulation system 2 (Cork) and 134 €/m² for the insulation system 3 (Rock Wool). The median values of the PB vary from 4 years for the insulation system A to 8 years for the insulation system B and 5 years for the insulation system C.

As expected, the energy tariffs impact the GC and PB values: lower costs are guaranteed in the electricity scenario, followed by gas and finally oil. This is due to the low overall heating efficiency defined for the oil scenario and the high one for the electricity scenario, together with the different energy tariffs in Italy. Furthermore, oil scenario entails the higher uncertainty (higher sd), due to the high uncertainty range defined for the equipment efficiency.

Furthermore, the GC mean values obviously increase by increasing the calculation period and this is verified also for the standard deviation, due to the higher uncertainty related to the future projections.

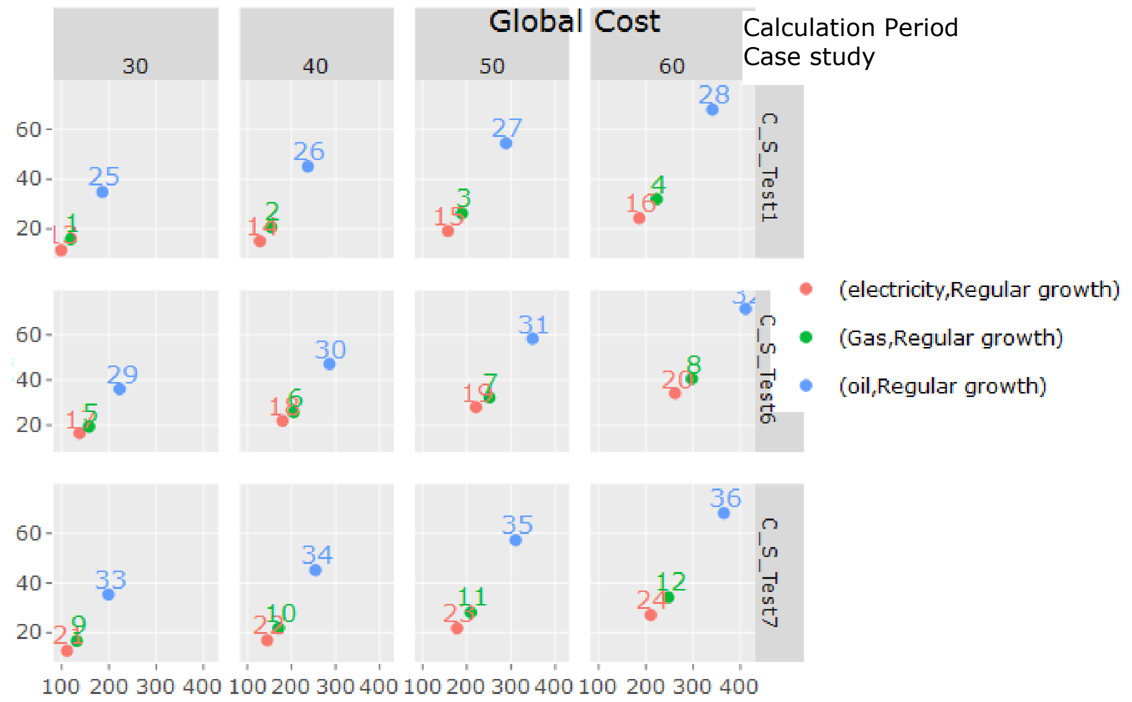

Figure 3. Global cost mean value (x-axis) and standard deviation (y-axis). The columns represent the different cp, while the rows the different insulation systems. Colours represent the energy sources.

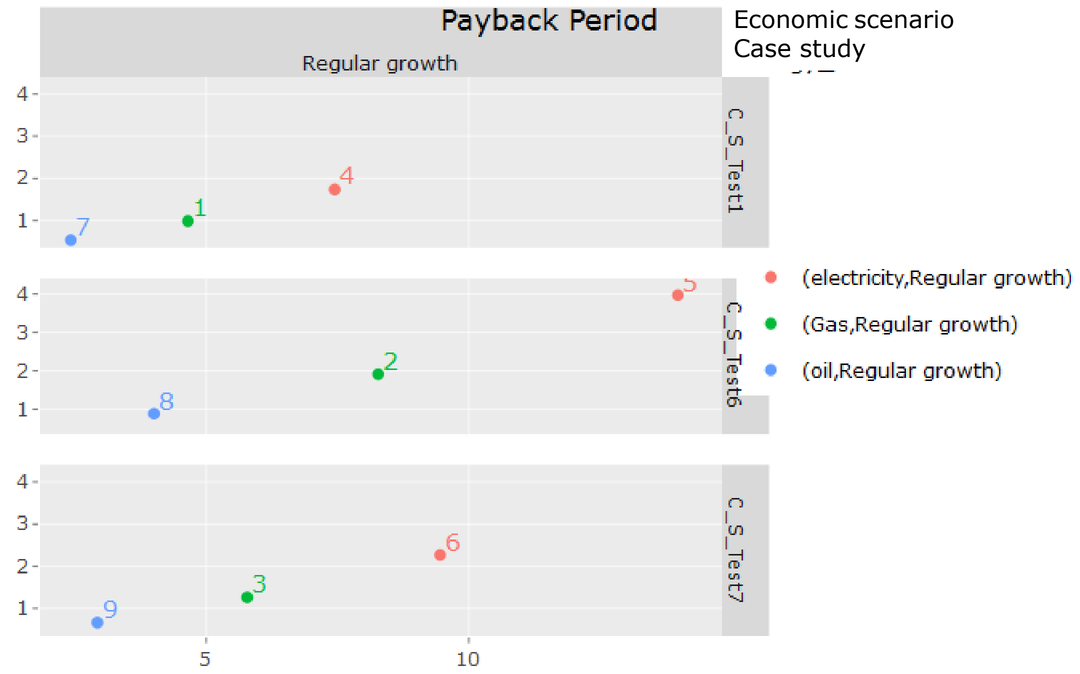

Figure 4. Payback period mean value (x-axis) and standard deviation (y-axis). The rows represent the different insulation systems. Colours represent the energy sources.

5. CONCLUSIONS

This paper presented a “probabilistic” approach to LCC and its application to an historical building case-study, to demonstrate how decisions on energy retrofit measures of historical buildings, related to their possible monetary costs and benefits, may be affected by a high uncertainty.

The sensitivity analysis performed show that the uncertainty on the economic outcomes is mainly due to the macro-economic parameters (in particular to the interest rate), whose future trends are difficult to forecast. This is particularly true in the case of historical buildings, for which long calculation periods are often taken into account.

Even if applied to a simplified case-study that only considered the wall renovation, the research wants to assert the necessity of improving decision tools that may include uncertainty and sensitivity analysis as part of the design process related to the energy retrofit of historical buildings. This would improve the reliability of LCC-based decision making, overcoming the evident limitations of traditional deterministic LCC approaches.

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