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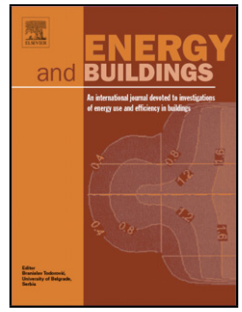

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Probabilistic Life Cycle Costing of existing buildings retrofit interventions towards nZE target: methodology and application example

Elisa Di Giuseppe*, Monica Iannaccone*, Martina Telloni, Marco D'Orazio*, Costanzo Di Perna**

* DICEA – Department of Construction Civil Engineering and Architecture, Università Politecnica delle Marche, Via Brecce Bianche 12, Ancona, 60131, Italy

** DIISM - Department of Industrial Engineering and Mathematical Sciences, , Università Politecnica delle Marche, Via Brecce Bianche 12, Ancona, 60131, Italy

Elisa Di Giuseppe, e.digiuseppe@univpm.it<mailto:e.digiuseppe@univpm.it>, +39-071-2204380

Highlights

- Poor reliability of input data reduce application of deterministic LCC methods
- A probabilistic LCC method via Monte Carlo approach is developed
- The method is applied to several building retrofit scenarios sighting the target nZE
- The resulting Global Costs are evaluated based on their probability distribution
- Sensitivity analysis is used to establish the most influential input parameters

Abstract

One of the major challenge facing the achievement of nZE standards in existing buildings is the economic issue: the evidence of monetary gains of energy savings facing high investment costs seems still rather limited to the investors' eyes. In this context, LCC methods have gained much importance in recent years. However, they present a limitation due to the notable simplifications and hypothesis usually made for input parameters that may affect the results.

In order to overcome this limit, this work suggests a probabilistic LCC based on uncertainty and sensitivity analysis via Monte Carlo methods and illustrate it through a building case study under several retrofit scenarios sighting the target nZE. The methodology allows investigating the economic effectiveness of alternative measures, giving insight into possible ranges of the economic indicator related to a specific design option. The analysis is focused on a micro-economic dimension and based on the availability and reliability of inputs data and on their proper characterization with Probability Density Functions. Variance-based methods for sensitivity analysis are employed to establish the most influential parameters on output uncertainty. The paper demonstrates the potentials of a probabilistic LCC in providing a more realistic decision support about investments for energy efficient projects.

Keywords

nZEB; building retrofit; energy efficiency; Life Cycle Costing; Global Cost; probabilistic assessment; Monte Carlo; uncertainty analysis; sensitivity analysis

Nomenclature

EPBD	Energy Performance of Buildings Directive

nZEB	Nearly Zero Energy Buildings	
EEM	Energy Efficiency Measure	
RES	Renewable Energy Sources	
LCC	Life Cycle Costing	
PDF	Probability Density Function	
CFD	Cumulative Distribution Function	
RS	Renovation Scenario	
RC	Renovation Case	
PV	Photovoltaic	
MEV	Mechanical Extraction Ventilation	
XPS	Extruded Polystyrene	
VIP	Vacuum Insulation Panels	
DHW	Domestic Hot Water	
BRS	Basic Random Sampling	
SA	Sensitivity Analysis	
STi	Total order Sensitivity indices	
H'T	Total envelope transmission heat transfer coefficient	[W/m^{2}K]
EPH,nd	Energy needed for heating	[kWh/m^{2}year]
EPH,nren	Net primary energy for heating	[kWh/m^{2}year]
EPH,ren	Primary energy for heating from on-site renewable sources	[kWh/m^{2}year]
EPgl,nren	Net global primary energy	[kWh/m^{2}year]
EPgl,ren	Global primary energy from on-site renewable sources	[kWh/m^{2}year]
EPgl,tot	Global primary energy use	[kWh/m^{2}year]
$C_g(t)$	Global Costs	[€]
t	Time	[years]
j	Building component	[-]
C_I	Initial investment costs	[€]
C_{sl}	Indoor surface loss costs	[€]
C_a	Recurrent costs	[€]
$R_{disc}(i)$	Discount rate	[-]
i	Year	[years]
Val_F	Residual value	[€]
R_R	Real interest rate	[-]
R_i	Inflation rate	[-]
R_{int}	Interest rate	[-]
L	Lifespan	[years]
C_M	Maintenance costs	[€]
U	Thermal transmittance	[W/m^{2}K]
η	efficiency	[-]

1. Introduction

The goal "Zero Energy" for new buildings appears increasingly accessible to all. The awareness of the benefits in energy and environmental terms, the significant progress of technologies, the more and more developed performance assessment methods facilitate the achievement of this target, established by legislative frameworks in several Countries.

In Europe, the 2010 Energy Performance of Buildings Directive (EPBD recast) [1] clearly established that all new buildings must be nearly Zero Energy Buildings (nZEB) by 31 December 2020 (public buildings by 31 December 2018). In US, the target of Zero Energy buildings is supported by the Department of Energy. Its "Planning for Federal Sustainability in the Next Decade", issued in March 19 2015 [2], set the goal of all new federal buildings achieving zero-net-energy by 2030. Several definitions of NZEBs are discussed and proposed at the international level [3,4], e.g. within the International Energy Agency (IEA) Task 40: Towards Net Zero Energy Buildings, comprising almost 20 countries [5].

Nevertheless, in the industrialized countries, building turnover rate is quite low. In Europe, the annual growth rate of new buildings is currently estimated at around 1-1.5% of the housing stock [6]. The impact of new nZEBs on the reduction of energy consumption and CO2 emissions is then quite limited in the nearest future.

Considering that in Europe 80% of the 2030 building stock already exists and today 30% of buildings are historical buildings that ought to last for decades, there is great potential for energy savings and consequently C02 emissions reduction exploitable in existing buildings. More attention should be then given to the strategies and technologies to convert existing buildings into nZEBs in different climates and conditions. Building energy renovation towards Zero Energy scenarios is today a strongly impacting strategy in the building sector to achieve effective energy saving [7,8].

EPBD recast requires that Member States shall draw up national plans and develop policies and measures in order to stimulate the transformation of buildings that are refurbished into nearly zero-energy buildings. Furthermore, on July 29th 2016, the European Commission released its guidelines for the promotion of NZEBs, recommending that Member States should focus on the refurbishment of existing building stocks towards NZEBs levels [9].

Achieving nZE standards in existing buildings usually means a two step-approach aimed to reduce the need for energy use by adopting Energy Efficiency Measures (EEMs) and provide the remaining energy needs through Renewable Energy Sources (RES). However planning nZE existing buildings may face even further and harder challenges than in new buildings, from several points of view [6,10]. Among them, the need for a deepen and accurate energy audit process, in order to exactly know the "as-built" situation in term of envelope and equipment features and building user-behaviour [11,12]. Then, the presence of several constraints (architectural, cultural, social, structural, etc.), that oblige the intervention to respect the integrity, authenticity and compatibility between the old and the new materials and techniques [13,14]. In addition, the definition of proper and effective EEMs for renovation, specifically designed and optimised for the energy efficient retrofitting of existing and occupied buildings [15,16], also taking into account the customer behaviour [17,18]. Finally, the lack of consolidated, comprehensive, systemic policies able to include the cost-savings and environmental impact issues implemented with a life-cycle perspective, even if several research and demonstration efforts for the development of an overall approach to building retrofit has be done in more recent years [10,19–21].

One of the major challenge facing the achievement of nZE standards in existing buildings is the economic issue [22–26]. Barriers such as high investments, long payback periods and perceived credit risk hamper buildings energy renovation [24,27,28]. The additional boost to the realization of nZEB seems requiring so high investment costs which may be not justifiable with the reduced consumptions (and costs) during the use phase. The evidence of economic gains of energy efficiency investments in existing buildings seems still rather limited [29]. Consequently, many customers see high operating costs and poor environment as an acceptable alternative to the time-consuming, disruptive and risky renovation process [30].

Life Cycle Costing (LCC) could then be an important decision support, to investigate benefits and risks of the investments in the building renovation sector. It practically allows choosing the most profitable design option, providing the total expected costs and benefits (expressed in terms of money) due to the application of alternative EEMs, evaluated during an established time frame and adjusted for the time value of money.

The importance of using Life Cycle Costing in the building sector has been attested at regulatory level in Europe by Directive 2010/31/EU, which established that Member States shall calculate “cost-optimal levels” of minimum energy performance requirements using a comparative methodology framework according to the consequent Commission Delegated Regulation and its Guidelines [31,32] based on EN 15459:2007 [33]. “Cost-optimal level” means the energy performance level which leads to the lowest cost during the estimated economic lifecycle, where the lowest cost is determined taking into account energy-related investment costs, maintenance and operating costs including energy costs and savings. As underlined by Ferreira et al. [34], “Cost optimality” and “nearly zero-energy buildings” are related concepts. If these approaches result in major differences in the selection of the best package of retrofit measures (one more focused on costs, while the other more concerned with low energy consumption and on site-renewable energy harvesting), then the transition from the cost-optimal concept to nearly zero-energy buildings might be problematic.

Cost-optimal calculations have been subsequently implemented in Europe at national level in compliance with the Directive, and are becoming more and more familiar to individual designers, investors, practitioners. A considerable amount of research uses LCC methods to assess the economic impacts of several EEMs for building design and renovation (examples are reported in

[20,34–41]). However, in many studies, in respect of a significant effort in the identification and parameterization of EEMs and in the evaluation of the related energy performance, the cost-optimal calculation is achieved with notable simplifications, mainly related to the cost items selection and quantification and in the forecast of macroeconomic variables.

In reality, the practical application of LCC methodologies is not straightforward. Accurate cost analysis rely on quality of data and long-term forecasts, and data uncertainty is a well-recognised matter associated with LCC methods [26,27,42–48]. Poor availability and reliability of input data increase the result uncertainty and could limit the LCC application. Ignoring these uncertainties may led to improper decisions, based on faulty assumptions [45]. LCC methods may still be useful in practice if the decision maker is aware of their inherent limitations [43].

Sesana and Salvalai identify as main problems in buildings LCC: the lack of reliable information; the difficulty in forecasting time factors over a long period (life cycles, future operating, maintenance and demolition costs and discount rates); the variability of construction costs of the same component or materials (depending on the company, the quantity and the availability in the specific context, etc.) [26]. Gluch and Baumann extensively discuss the theoretical assumptions and the practical usefulness of the LCC approach in making environmentally responsible investment decisions [43]. They underline that LCC's practical usefulness is constrained by its oversimplification to a monetary unit, the lack of data, the complexity of the building process and the conceptual confusions. Recently, Ilg et al. provide a comprehensive overview of uncertainties in LCC [49]. They try to systematize the sources and types of uncertainty and conclude that the variety of uncertainties makes it difficult to provide a meaningful and simple categorization.

Some other researches propose methods to address LCC uncertainty. Almeida et al. [50] suggest an integrated methodology that quantify and include building energy performance assessment uncertainty in LCC estimation. The methodology relies on Monte Carlo simulation to calculate statistical distributions of energy demand. The associated costs distributions are then introduced in an LCC analysis, while the other LCC parameters are considered as deterministic, in certain respects similarly to [47,51]. Burhenne et al. develop a methodology for uncertainty quantification mainly applied to building energy simulation, but also addressing cost-benefit calculation [45]. In particular, they use ARIMA (auto regressive integrated moving average) models to predict future values of the macroeconomic variables, revealing through an example case that the technical parameters have much less influence on the LCC outcome than the economic parameters. To our knowledge few other studies applied in practice methods to address uncertainty in buildings LCC analysis [52,53], and always limited to few types of data inputs uncertainties. A comprehensive and global approach to the issue is still missing.

In this context, the present paper proposes a LCC probabilistic methodology based on uncertainty and sensitivity analysis via Monte Carlo (MC) approach (whose potential and effectiveness in several engineering applications is already widely documented, e.g. in [54]). The methodology allows comparing alternative EEMs based on their primary energy demand and Global Costs, by establishing the level of confidence that an EEM performs better than another one, or identifying the best performing alternative minimizing the likelihood of exceeding cost thresholds. The methodology is illustrated through a building case study under different energy renovation scenarios sighting the target nZE.

One contribution of this paper lies in the identification and characterization of the main stochastic inputs typically involved in the Global Cost method established by Standard EN 15459 (related to the initial Investment Costs, Annual Costs, Residual Values and Discount Rates). The analysis is focused on a micro-economic dimension (the typical perspective of a private investor, designer, householder) and based on the availability and reliability of inputs data and on their proper estimates.

Another contribution is the quantification of the uncertainty of the outputs as a result of possible variance of the input parameters through variance-based methods for sensitivity analysis, which allow establishing the most influential parameters and which parameter variations can be neglected. The identification of the key inputs eventually provides focus to further data gathering activities to support the analysis.

Probabilistic LCC assessments in building sector would provide a more realistic decision support about investments for energy efficient projects during the design phase, giving insight into possible ranges of the economic indicator of a specific design option. This paper wants to be a contribution in the field, but further research developments are already identified in the conclusions.

2. Methodology

The probabilistic Global Cost assessment of energy efficiency measures proposed in this work includes uncertainty propagation and sensitivity analysis via Monte Carlo methods. While a deterministic LCC analysis approach requires input variables that are fixed in their "deterministic" value, in Monte Carlo approach variables are modelled using a Probability Density Functions (PDFs) and the quantification of the uncertainty of the outputs is a result of possible variance of the input parameters. MC method consists in randomly selecting input variables (or using sampling schemes) and inserting them into the output-equation a proper number of times, depending on the envisaged accuracy level, to predict the corresponding output distributions. The uncertainty analysis is the study of the model output distribution as a function of the input parameters' distribution. Sensitivity analysis (SA) allows to relate the output variations to the input variations.

The probabilistic Global Cost methodology is then based on the following steps, also reported in Fig. 1 and described in the next sub-paragraphs:

1. Definition of the main hypothesis and system boundaries for the Global Costs calculation method based on EN 15459;
2. Identification and characterization of the PDFs of the stochastic inputs of the Global Costs calculation;
3. Uncertainty propagation and analysis through Monte Carlo methods (sampling based on Sobol sequences);
4. Sensitivity analysis through variance-based decomposition techniques (Sobol method).

The methodology is then further illustrated through the application to a building case-study (section 3) under three main Renovation Scenarios (RSs). The scenarios include several alternative Energy Efficiency Measures for the building envelope or equipments renovation, according to the Italian regulation on the energy efficiency of buildings and nZEB definition, for a total of 10 Renovation Cases (RCs). Results of the application are reported in section 4.

2.1 Global Cost calculation method

The LCC assessment of the EEMs is carried out based on the Global Cost method described in the European Standard EN 15459. The Global Cost equation has been slightly modified to take into account the indirect cost due to the building indoor surface loss (that grows with the internal insulation thickness) as in [55]. The Global Costs $C_g(t)$ referred to the starting year t_0 are then calculated by summing, for each building component j, the initial investment costs C_I, the indirect cost of the indoor surface loss C_{sl}, the recurrent costs C_a discounted by the rate $R_{disc}(i)$ for every year i, and the residual value Val_F, as reported in Eq.(1).

$$C_g(t) = C_I + C_{sl} + \sum_j \left[\sum_{i=1}^{t} \left(C_{a,i}(j) \cdot R_{disc}(i) \right) - Val_{F,t}(j) \right]$$

(1)

Inflation rate and interest rate affect the real interest rate R_R, according to Eq. (2):

$$R_R = \frac{R_{\text{int}} - R_i}{1 + R_i / 100}$$

(2)

The real interest rate R_R is used to calculate $R_{disc}(i)$ through the following Eq.(3):

$$R_{disc}(i) = \left(\frac{1}{1 + R_R / 100} \right)^i \qquad (3)$$

The initial investment cost C_I represents the construction/installation cost of the EEMs considered, and includes their purchase, transportation and installation. C_{sl} is calculated based on the loss in surface area and the buildings prices in the surrounding area. The recurrent costs C_a include annual costs such as components maintenance costs and energy carriers' costs. For the calculation of energy costs, the annual energy consumption, based on equipment efficiency and energy source typology, is coupled with the tariff for the energy carrier considered. The replacement costs of components are to be considered in recurrent costs too, with a frequency depending on the lifespan of the component concerned. At the end of the calculation period, the residual value Val_F of the components is calculated based on a straight-line depreciation of the initial investment or replacement cost of the component until the end of the calculation, discounted at the beginning of the evaluation period.

As the main objective of the evaluation is the comparison of different efficiency scenarios, the only investment cost items included in the LCC calculation are those related to the EEMs. Other expenses are therefore omitted from the calculation such as the costs related to building elements that have no influence on the energy performance and the costs that are the same for all the measures. VAT (Value Added Tax), technical costs, insurance, RES financial incomes, etc. are neglected in this assessment. Lastly, costs of greenhouse gas emissions are neglected because Global Costs calculation is performed in a «financial» perspective, while disposal costs are neglected because the calculation period is shorter than building lifetime (according with the European Commission Delegated Regulation). Hence, the cost categories included in the Global Costs calculation within this study are the following: Initial investment costs, Energy costs, Maintenance costs, Replacement costs.

The Global Cost calculation is directly linked to the duration of the calculation period t. The assessment in this study is carried out considering at first a reference calculation period of 30 years (as established by the European Commission Delegated Regulation and its Guidelines [31,32] for residential buildings) and then by varying the duration of the calculation period from 5 to 50 years, to determine its influence on the result.

2.2 Probabilistic Global Cost assessment

The MC based approach to Life Cycle Costing requires quantifying the Probability Density Functions of the model's input parameters to lead the calculation in probabilistic terms and perform the Monte Carlo simulation. As further described in the case study application, we characterize trough PDFs the following LCC input variables, based on available data sets, literature, time series, and, when data were lacking, on our expertise and judgement: (1) Inflation rate R_i, (2) Interest rate R_{int}, (3) Initial investment costs C_I, (4) Indirect costs C_{sl}, (5) Components Lifespan L, (6) Maintenance costs C_M.

Since the quality of the outcome (the PDF of Global Cost) is dependent on the number of simulations carried out and the sampling scheme used, in this work, we use Sobol's sequences 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. Indeed, the SA based on Sobol's variance decomposition approach imperatively needs the input sample generated by the Sobol sequences [56]. The number of model evaluations (sample size) depends on the number of variables [57]. The smallest sample size for the Sobol indices calculation is $n(2k+2)$, where n is the minimum model evaluations for estimating one individual effect; n takes the value of 16, or 32, 64…; k is the number of variables [57].

As a consequence of the procedure, the resulting Global Costs in the probabilistic analysis is to be evaluated based on its probability distribution. The likelihood of one EEM outperforming another can be evaluated by comparing the probability distributions or the cumulative frequency function of the alternatives.

Then through the SA, it is possible to obtain two sets of sensitivity indices for each 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 all variance caused by its interactions with any other input variables [58]. The higher the value of the sensitivity indices, the most influential are the related parameters of the model. In particular, the total order indices (STi) allow to cut-off those parameters presenting a very low value, which can be considered totally not influential for the output uncertainty and then fixed in their "deterministic" value. Since "importance" in SA is a relative notion and there are no established threshold for indices [59], we look at their absolute values and at the distance between them and consider as threshold the value of 0.05. Therefore, since SA allow establishing which parameters need accurate distributions and which parameter variations can be neglected, the model can then be updated to improve the calculation efficiency.

Data fitting for the uncertainty characterisation, sample generation, uncertainty propagation, and sensitivity analysis are performed through a data analysis software, R [60], a free software environment for statistical computing and graphics.

3. Building renovation case-study

The probabilistic Global Cost methodology is illustrated through a building case study under different energy renovation scenarios sighting the target nZE. The building is a single-family detached house (Fig. 2), built in 1935 in Cattolica, a coastal town in the centre of Italy (average heating degree-days: 2165). The building has two floors plus an attic, over a total net surface area of about 178 m^2. The original walls were made by plastered brick masonry with variable thicknesses, from 29 cm (U=1.76 W/m^2K) to 16 cm (U= 2.58 W/m^2K). Floors and roof consisted on wooden slabs with respectively pavement (U=1.29 W/m^2K) or clay tiles (U=1.68 W/m^2K). Original windows had timber frames and 4 mm single glazing (U=5.7 W/m^2K). The heating system consisted on a conventional natural gas boiler (23 kW peak power) and radiators.

3.1 Energy Efficiency Measures and performance assessment

In order to improve the building heating energy performance, three deep renovation scenarios (called "RS 1,2 and 3") were selected based on the actual requirements imposed by Italian regulation D.M. 26/06/2015 [61] for "first level renovation" interventions. According to the regulation (Annex 1), envelope renovation measures must affect more than 50% of the gross envelope surface area and the intervention must include the replacement of the heating and/or cooling system. Each RS includes alternative EEMs for the building envelope for a total of 10 renovation cases (RCs).

In general, RSs include high performance envelopes (both opaque and transparent components); reversible high efficient heat pumps and/or condensing boiler for heating and hot water; photovoltaic (PV) panels and solar collectors; high performance distribution, emission and control systems for heating; Mechanical Extraction Ventilation systems (MEV). Solutions were selected among market solutions really workable in this building typology and considering diversified levels of technological value and costs. RSs 1 and 2 address the minimum energy requirements for this kind of retrofit intervention in Italy, while RS 3 meets the requirements for a nZEB, as defined by Annex 1, section 3.4 of D.M. 26/06/2015, and provides the maximum amount of renewable sources as required by Annex 3 of the Italian regulation D.Lgs. 28/2011 [62].

Concerning building vertical opaque envelope, for RS 1 and 2, the U-value for the wall is lower than 0,30 W/m^{2}K, and for RS 3 than 0,28 W/m^{2}K, in compliance with the regulation. Furthermore, each RS include several alternative internal thermal insulation systems for the opaque vertical envelope (insulation material coupled with plasterboard), based on the following materials: XPS (solution A), cork (B), aerogel (C) and VIP (D), this latter only for RS3.

With regards to windows, three alternative solutions are proposed: wooden-metal frame double glass windows (U_w =1.61 W/m^{2}K, for RC 1B,2B,3B), PVC frame double glass windows (U_w =1.26 W/m^{2}K, for RC 1A,1C) and PVC frame high performance double glass windows (U_w =0.90 W/m^{2}K, for RC 2A,2C,3A,3C,3D).

Finally, concerning the building equipments, RS1 includes a heat pump and solar collectors for heating and domestic hot water and PV panels (0.87 kWp). RS2 and RS3 include an integrated system for heating and domestic hot water with condensing boiler (24kW), Heat Pump and solar collector, a MEV system, and PV panels (1.45 kWp). A radiant floor heating and a Direct Digital Control System for heating regulation are provided in all RSs.

Table 1 reports the main features and costs of each EEM included in the RCs.

The Building performance simulation for the assessment of the energy consumption related to all RCs was calculated based on the Italian technical specifications UNI/TS 11300 [63], which represent the national application procedure of the European technical standard EN 13790 [64], with the following assumptions:

- climatic data of Cattolica (climatic zone “E”, one of the most representative in Italy);
- ventilation rate at 0.5 vol/h;
- simplified approach for the calculation of internal heat gains, building internal heat capacity, temperature of unconditioned spaces, and thermal bridge effects (percentage increase of the transmission heat transfer);
- conversion coefficient to primary energy fixed at 1.05 for fossil fuels, 2.42 for electricity, 1 for thermal energy from solar collector, for heat pump and electricity from PV [61].

The results of the building energy simulations are reported in Section 4.1 and include: the annual energy needed for heating; the annual electricity and gas consumptions for heating, hot water and MEV; the annual energy provided by RES (PV and solar collectors); the annual primary energy for heating, hot water and MEV; the total envelope transmission heat transfer coefficient.

We underline that lighting and cooling consumptions are not taken into account in this study, considering that the building is located in a quite cold climatic area (Italian climatic zone E) and the retrofit interventions focus on the heating performance (envelope insulation and heating equipment). Nevertheless, the LCC probabilistic methodology developed can be replicated by considering other retrofit measures and energy uses.

3.2 Characterization of input uncertainty and probabilistic Global Cost assessment

The following LCC input variables were characterized trough PDFs: (1) Inflation rate R_i, (2) Interest rate R_{int}, (3) Initial investment costs C_I, (4) Indirect costs C_{sl}, (5) Components Lifespan L, (6) Maintenance costs C_M.

The stochastic character of the economic parameters depends on the extreme uncertainty of the financial market, whose evolution in the future is difficult to be exactly predicted. For this assessment, a "baseline" scenario has been considered, based on the analysis of inflation rate time series in Italy, in the period from the adoption of euro currency, when European Central Bank started its monetary policies that aim to preserve the inflation rates below but close to 2% over the medium term. For the interest rate, data were collected and analysed from a Bank of Italy survey on personal loans rates (fixed rate mortgages averaged over the 12 months of 2015 [65]), on the EURIRS 30 years average rate for 2015 [66] and on the usury limits in Italy.

The initial investment costs were determined through the analysis of regional and national pricing lists for public works and private companies' tariffs. In particular, with regard to envelope elements such as windows and insulation, the initial investment cost was considered as the sum of the three cost items: material, labour and transportation cost. Data on the labour cost were obtained comparing both a study of the Italian Labour Ministry [67] and price lists of specialized companies. The transportation cost was obtained from a study of the Italian Ministry of the Infrastructures and Transports on the operating costs of transport trucking companies [68]. In order to assess the impact of the investment costs on the global costs, we selected technological solutions with highly diversified costs, i.e. XPS insulation vs aerogel insulation, PVC windows frame vs wood-metal windows frame. Concerning the heating plant initial investment cost, data were obtained from private companies' price lists, considering their geographic variations.

For the cost of indoor surface loss due to the internal insulation, the calculation was based on buildings sales prices in Cattolica area coming from the Italian Revenue Agency [69].

Data on envelope (opaque components) lifespan were taken from INIES database [70]. Specifically, as internal insulation solutions are composed by pre-coupled plasterboard and insulation, the only service life of external layer (plasterboard) was considered as the reference lifespan (30 years). Data on windows lifespan were taken from specific studies [71,72]: a deterministic value of 25 years was assumed for PVC windows and of 40 years for wooden ones, and their variations described by Weibull distributions (this type of PDF is considered the best to fit the behaviour and the decay of a material as a function of time [73]). Finally, data on heating equipment lifespan and related uncertainties came from producers technical reports or ASHRAE database [74].

The maintenance costs were assumed based on market surveys (for envelope components), and Annex A of EN 15459 (for building equipments). With regard to the maintenance uncertainty, it was based on the geographic variability of the labour cost.

Table 2 summarizes the uncertain inputs considered in the calculation and the related references for standard values and probabilistic values. Table 3 reports the PDFs obtained for the stochastic input parameters of the Global Cost calculation.

The results of the energy performance assessment (section 4.1) have been used to achieve the energy carriers' costs, according to the specific energy source used and national tariffs (Italian current prices applied for calculations are 0.161668 €/kWh for electricity and 0.706999 €/m³ [75] for natural gas, data of October 2016), and perform the Global Cost calculation. The energy costs are considered as deterministic input in this work.

At first a "deterministic" Global Cost calculation was performed (section paragraph 4.1) taking into account the standard values of input data for each scenario during different calculation periods.

Sobol's sequences technique was then used to generate samples from the input PDFs and perform the probabilistic assessment according to the methodology developed. A first attempt with a sample size of 6912 draws was generated and the efficiency of the sampling strategy was assessed by comparing the PDFs of the output sample with a reference Basic Random sample (BRS) simulation at high number of runs (20000).

The probability distributions and the cumulative frequency function of the resulting Global Costs in all RCs were then assessed and compared (section 4.2). Finally, the Sensitivity Analysis was performed (section 4.3).

4. Results

4.1 Energy performance assessment of Renovation Cases and deterministic Global Cost calculation

Table 4 provides the main results of the energy performance simulations for each RC: the total annual energy produced from RES and energy needs and consumptions (electricity and natural gas) in terms of heating, DHW and ventilation. The three main RSs entail a significant reduction of the annual primary energy use of the building and this underline the great benefits deriving from the application of low energy technologies.

The energy needed for heating is about 60-64 kWh/(m²y) in RS 1, 56-58 kWh/(m²y) in RS 2 and 47-50 kWh/(m²y) in RS 3 (nZE scenario), according to the different performance of the building envelope among scenarios. The slight differences within each scenario are due to the different values of envelope thermal transmittance and heat capacity achieved in relation to the different insulating materials used. Concerning the total primary energy, RS1 and RS2 are around 87-92 kWh/(m²y), while nZE RS3 is around 80-83 kWh/(m²y). In RS 1 there is no consumption of natural gas, as the heat pump requires only electrical energy; while in RS 2 the hybrid system does require natural gas for the condensing boiler when the heat pump or solar collectors are not sufficient to ensure the thermal requirements, especially in winter with the lowest temperatures (in that area the project temperature is -2 °C). RS 2 have a slight drop in consumptions due to the use of the MEV.

In RS 3, the nZE scenario, the higher envelope thermal resistance determines the slowest consumptions. The annual PV energy productions are about 590-837 kWh for RS 1 and 1340-1465 kWh for RSs 2-3. These productions can supply at least 50% of the annual energy demand for heating and DHW, fulfilling the minimum Italian standards, also valid for nZEB.

The recent European Guidelines for the promotion of nZEBs released on July 29th 2016 provided the benchmarks for energy performance of nZEBs, classified by several climatic zones in Europe. Targets for a new residential building in Continental climate (as in Cattolica area) are: consumption of total primary energy of 50-70 kWh/(m^{2}y), of which 30 kWh/(m^{2}y) from on-site renewable sources and 20-40 kWh/(m^{2}y) for net primary energy. The building case study presents slightly higher values but this is justified by the fact that it is an existing building subjected to a renovation and not a new construction.

Fig. 3 shows the “cost-optimal” graph, that is the $C_g(t)$ for building unit surface area against the building total primary energy consumption, for each RC considered. Global cost varies from 764 €/m² in RC 1A (with XPS insulation) to 1345 €/m² in RC 3C (nZE Scenario with Aerogel insulation). Both RSs 2 and 3 present the same building equipments, the only difference between the two scenarios, which determines the increasing cost and decreasing consumption, is due to envelope thermal resistance, and consequently insulation level. RCs to the left of the graph (nZE scenarios) are those that entail lower energy costs during building operating phase facing higher investment costs, as clearly understandable from Fig. 4, which reports each cost item of the $C_g(t)$ assessment during the same calculation period (components residual values are deducted from investments costs).

Fig.4 highlights that the initial investment costs are the predominant cost items in this calculation period (for all RSs around 38-64% of the deterministic $C_g(t)$). They are particularly significant in those scenarios with more expensive insulation systems (C-Aerogel, D-VIP). Indeed, the cost of the surface loss due to internal insulation installation has an inverse trend because generally expensive insulations require a lower thickness due to their higher performance (from 21% in A scenario to 4% in D scenario). The maintenance costs have a lower – but always considerable - impact on the $C_g(t)$ (13-23%). During the established calculation period, only a limited part of the building envelope and equipments need replacement (due to their lifespans). Consequently, replacement costs are quite low. Results would be different if we select a longer calculation period (already from the "thirtieth" year, when the whole building insulation replacement would occur). Finally, as expected, the energy costs are the lower cost items and decline gradually from 13% to 4% in nZE scenario (3C).

All RCs provide a high reduction of primary energy; 3A scenario is the one with good energy performance and lowest investment costs (37%) among nZE scenarios. It must be noted, however, that this insulation type (XPS) has economic advantages in investment costs but not for indirect costs, since it entails a considerable loss of surface area. Solution 3D (with VIP insulation) provides a very good energy performance at low $C_g(t)$.

Within the nZE RS 3, Fig. 5 represents the Global Costs trend during a variable calculation period from 5 to 50 years, for the four alternative RCs. It can be noted a remarkable jump in costs between 30 and 35 years, due to the whole replacement of the envelope insulation. This increase is wider with the higher investment costs of the insulation (C-Aerogel solution, in particular). This representation provides a better understanding of the possible impact of replacement costs on the economic assessment results. The jump is less evident for the cheaper insulation solutions (A-XPS, B-cork).

4.2 Probabilistic Global Costs calculation

In order to assess if the chosen sample size of these PDFs (established within Sobol's sequences) was sufficient to guarantee the quality of the outcome, the PDF of the output sample was compared with the result of the reference BRS simulation at 20000 runs. The convergence of the mean and the standard deviation of the output samples has been investigated for the calculation period of 30 years, obtaining a percentage difference of 0.01% for the mean and 0.09% for standard deviation. The good convergence of the results is clearly shown by the PDFs of all RCs obtained with Sobol sampling and BRS simulations, represented in Fig. 6.

For RS 1, the median of the $C_g(t)$ varies from a minimum of 803 €/m² for XPS RC (1A) to a maximum of 1107 €/m² for Aerogel RC (1C). Similarly, for RS2, it varies from a minimum of 946 €/m² for XPS RC (2A) to a maximum of 1193 €/m² for Aerogel RC (2C). Scenario 3 presents the higher $C_g(t)$, with a minimum of 1029 €/m² for XPS RC and a maximum of 1414 €/m² for the Aerogel RC.

Fig.6 also includes the cumulative distribution functions (CFDs) of $C_g(t)$ in all the RCs. The CFD representation is a useful mean to identify the Global Cost range given any probability and recognizing the best performing alternative minimizing the likelihood of exceeding cost thresholds. E.g., in this case-study, with a likelihood of 90% in the nZE scenario, $C_g(t)$ of cases 3A and 3B (respectively with XPS and cork insulation) should be under 1300 €/m², while in RC 3C around 1800 €/m² for the same probability threshold.

In Fig.7, probabilistic Global Costs for each RC at the calculation period of 30 years are represented through Box-Whiskers plots in order to better visualize the median values obtained and related interquartile ranges. Some remarks arise from the graph, which require supplementary investigations through the sensitivity analysis. In particular:

- Renovation cases "C" (those that include aerogel internal insulation solutions) within each main RS always entail the wider uncertainty range.
- The Global Costs uncertainty increases progressing towards the best performing RS, so with the increasing of the investment costs.

A further observation can be drawn from Fig.8, that reports the probabilistic $C_g(t)$ trend for RS3 during a variable calculation period from 5 to 50 years, similarly to the deterministic graph reported in Fig 5: the outcome uncertainty increases with the calculation period.

4.3 Sensitivity Analysis

This section reports the results of the Sensitivity Analysis (calculation of First and Total order indices through Sobol method) performed for the $C_g(t)$ assessment for each RC and during three calculation periods: 10, 30, 50 years.

STi for each RC, are reported in

Table **5** by way of example for the only calculation period of 30 years, while are extensively represented by histograms in Fig. 9 for the three calculation periods (10, 30, 50 years). In table, black numbers represent the STi over the established threshold of 0.05 (the uncertainties in the input parameters that have more influence on the variance of output), while grey numbers represent those under the threshold (uninfluential parameters).

From the table and figure, it is clear that macroeconomic inputs (inflation rate and interest rate) are the most influential parameters in all RS and calculation periods considered. In the $C_g(t)$ equation, they affect all the cost items (replacement, maintenance costs and energy costs) through the discount rate, and have the wider uncertainty ranges due to the difficulty in their future forecasting.

In all calculation periods and RSs, the uninfluential parameters are: all components maintenance costs, windows investment and replacement costs, the lifespans of heating terminals, photovoltaic system and regulation equipment.

Going into detail for each RS, with regard to RS1 (Fig. 9a), the most influential parameters (excluding the macroeconomic variables) are the heating and DHW generation lifespan, in particular for the calculation period of 10 years. Another important factor is the insulation lifespan at 30 years. This last parameter is even more important for those scenarios with expensive insulation systems (C scenarios). The importance of these parameters is explained by the fact that the calculation period is comparable to the replacement period. A similar situation is achieved in RS 2 and 3 (Fig. 9b and 9c), where, however, some other parameters uncertainties have an impact on the output variance: the insulation and equipment investment costs and the MEV lifespan. Finally, indoor surface loss is generally an influential factor for the shortest calculation period (10 years), as it is considered as an “added” investment costs, and in particular for RCs with the highest insulation thicknesses.

In order to deepen the relationship between the most influential factors and the calculation period, Fig. 10 reports summary graphs of the STi trends during the three calculation periods.

Concerning the macroeconomic parameters (inflation and interest rates, respectively in Fig. 10 a and b), their influence on the output variance is generally growing with the increasing of the calculation period. The RCs C (those with Aerogel insulation) are an exception in this trend. Their STi slightly decrease at 30 years and then grow between 30 and 50 years. This phenomenon is due to the fact that in C scenarios at 30 years other influential factors come into play, as insulation cost and lifespans, reducing the importance of macroeconomic variables.

With regard to the insulation investment costs and lifespans (respectively in Fig. 10 c and d) a particular trend can be observed: STi are generally higher at 30 years. This is due to the fact that insulation solutions have an average lifespan of 30 years; consequently, in correspondence of that calculation period, the possibility to include the insulation replacement costs depends on the input drawn during the probabilistic assessment. This is even more evident for C scenarios, whit the most expensive insulation solutions (aerogel).

5. Conclusions

One of the major challenge facing the achievement of nZE standards in existing buildings is the economic issue: the evidence of monetary gains of energy savings facing high investment costs seems still rather limited to the investors' eyes. In this context, LCC methods have gained much importance in recent years. Nevertheless, they present a limitation due to the notable simplifications and hypothesis in the input parameters that may affect the results. In order to overcome this limit, the present work proposed a LCC probabilistic methodology based on uncertainty and sensitivity analysis via Monte Carlo approach, for the assessment of the economic performance of alternative building energy efficiency measures. A probabilistic assessment would provide a more realistic decision support, giving insight into design robustness and possible ranges of the economic indicator of a specific design option. The main contributions of this work in the field concern (1) the process of identification and characterization of the main stochastic inputs typically involved in the Global Cost method and (2) the Sensitivity Analysis implemented to establish the impact of input uncertainties on the output variance.

The work aimed to highlight the potential of these types of methods through the application to a building case study under different energy renovation scenarios sighting the target nZE.

The results obtained on the case study highlighted some issues that still separate "cost optimality" and "nearly zero-energy buildings" concepts. The initial investment costs are the predominant cost items in energy efficient buildings, where the annual energy costs are quite low, if the assessment is performed in a medium-short calculation period as 30 years. For all renovation scenarios, investment costs are around 38-64% of the Global Costs, depending on the value of the technological solution used, while heating costs decline gradually from 13% in RS 1 and 2 to 4% in nZE scenario. The use of super insulation materials allows reducing the indirect costs due to the loss of internal surface, an important issue for the retrofit of existing and historic building with valuable facades. Nevertheless, that advantage does not reward these solutions in the context of the global costs, which are strongly affected by the highest investment costs.

Furthermore, considering the probabilistic approach developed, the Global Costs uncertainty increases progressing towards the most efficient scenarios. In these cases, the output variance is strongly affected by the variance of the investment costs and the lifespans of the most expensive solutions (higher sensitivity indices).

A calculation period of 30 years is usually considered a reference time for LCC, when the investor is interested in calculating the possible return on investment. However, the interest to carry out efficiency measures that prefigure the nZE target can be fully appreciated if longer periods are taken into account. Possible ways to bridge the gap between “cost optimality” and “nearly zero-energy buildings” must therefore be sought in the implementation of effective interventions, but at lower costs and with more guarantees on their durability in time.

Even if the results obtained are related to a specific case study, some general findings can be drawn foreshadowing future developments for the probabilistic approach to LCC.

In this study, we have pursued the idea of considering a “baseline” macroeconomic scenario, with PDFs of economic variables coming from the analysis of related time series of last years. Such approach involves high uncertainty margins for these variables and consequently a great influence on the result variance (highest sensitivity indices in all scenarios). A consistent development of the methodology could be the evaluation of several alternative economic scenarios rather than one baseline scenario with wide margins of uncertainty. These scenarios would represent alternative general macroeconomic conditions. The sensitivity analysis could then be performed within each scenario in order to verify the outcome robustness.

Furthermore, the study highlighted the importance of components lifespans, because of the significant impact of the possible replacement costs on the results, and a particular trend for the related sensitivity indices, due to the input drawn during the MC process when the component lifespan is close to the selected LCC calculation period. With this regard, further research is needed to properly characterize the lifespan PDFs of different building technologies and thoroughly investigate their impact in different case studies.

Finally, in this study the building energy performance was considered as a deterministic input in the Global Cost calculation, while future sensitivity analysis could also include the impact of its uncertainty.

The practical application of comprehensive probabilistic LCC assessments is a research field still barely explored, but with a great potential in order to overcome the perceived (often not really counted) economic risk, which today hamper buildings energy renovation.

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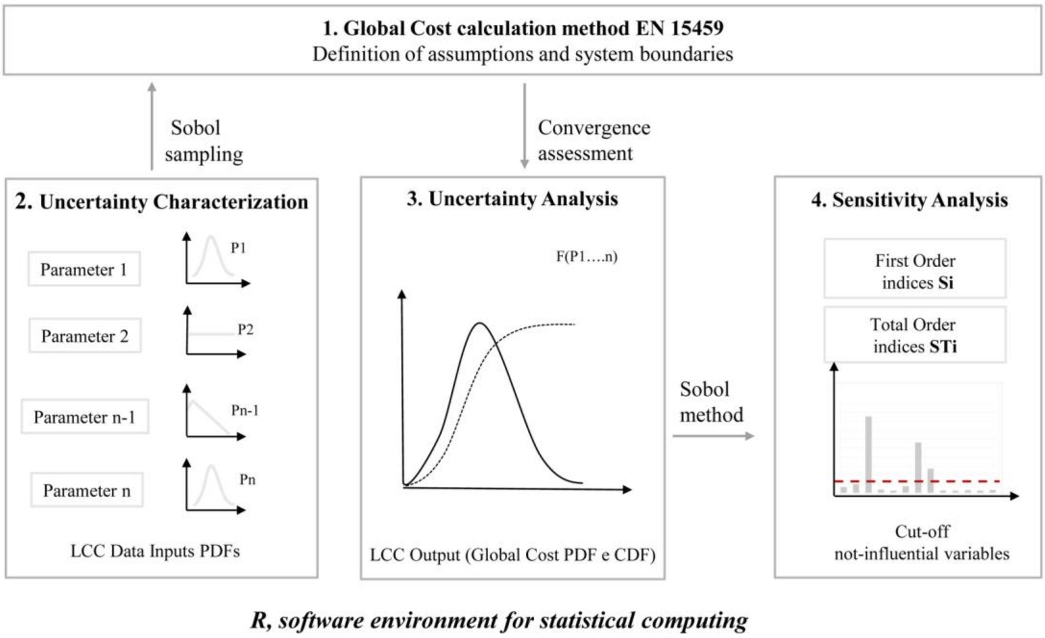


Fig. 1. Diagram of the MC based methodology for LCC probabilistic assessment.

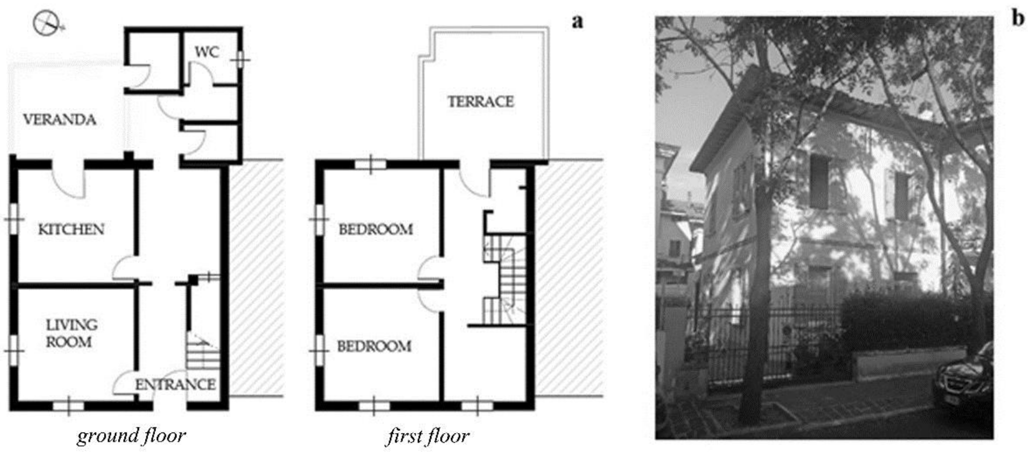


Fig. 2. Building case-study. (a) Plans; (b) View of the north facade.

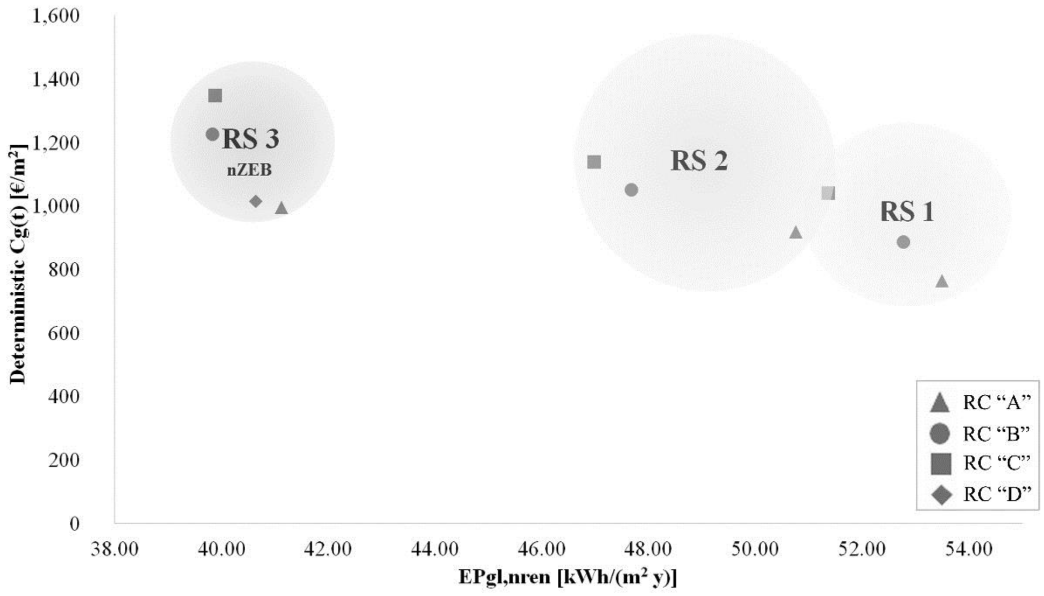


Fig. 3 Deterministic cost-optimal assessment for each Renovation Case during a calculation period of 30 years.

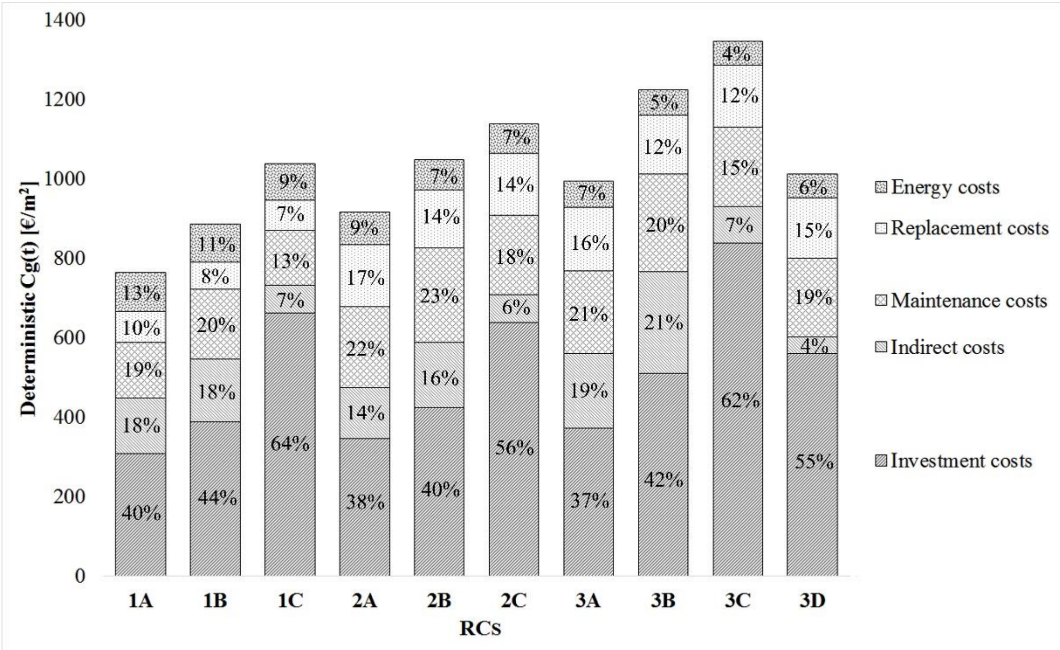


Fig. 4 Individual cost items of the deterministic Global Cost assessment for each Renovation Case during a calculation period of 30 years.

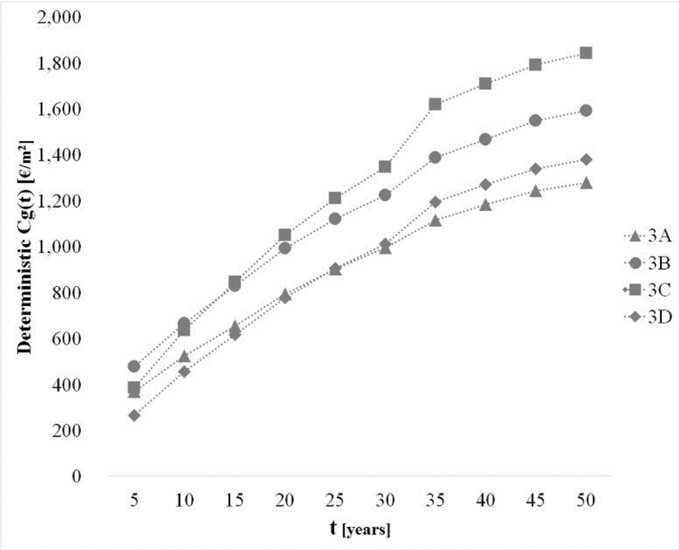


Fig. 5 Global Costs trend during a variable calculation period from 5 to 50 years, for the four alternative cases of renovation scenario 3 (four different internal insulation solutions).

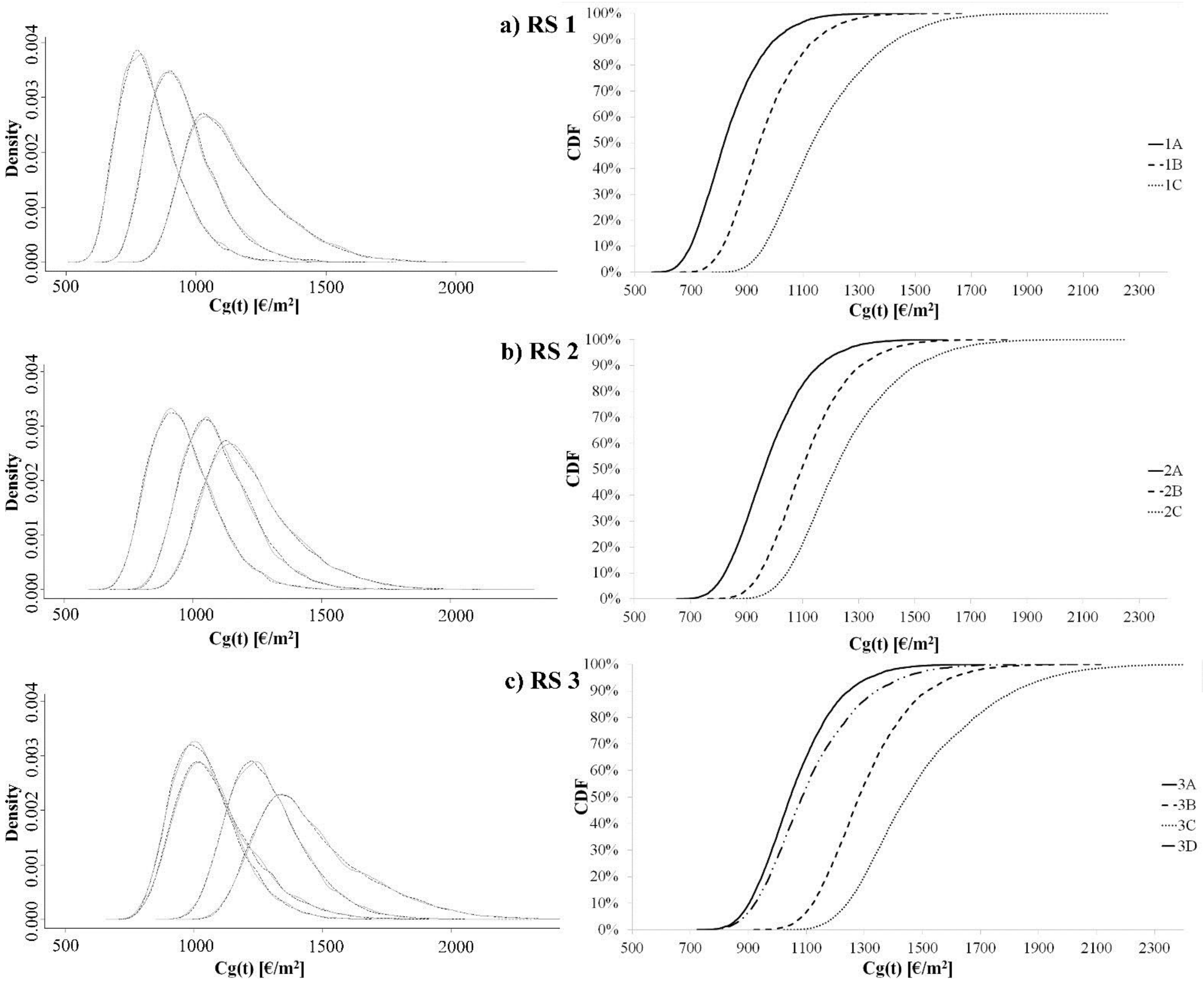


Fig. 6 Probabilistic Global Costs for the Renovation Scenarios during a calculation period of 30 years. Probability Density Functions obtained from the Sobol sampling and the reference BRS simulations, and Cumulative Distribution Functions.

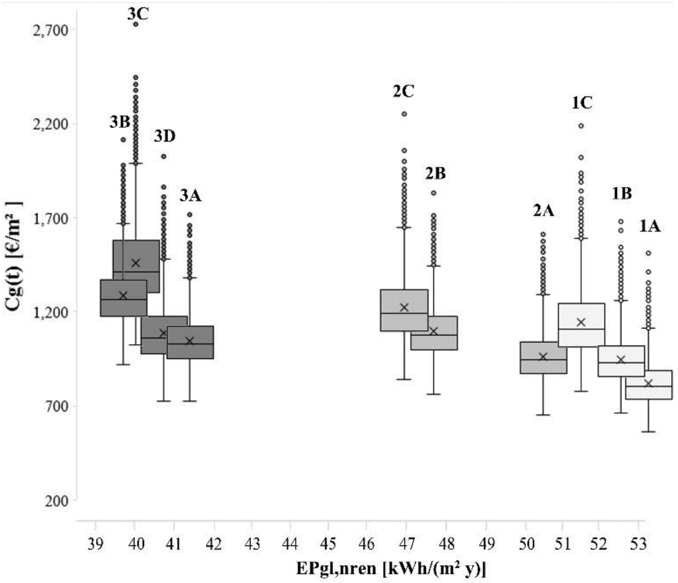


Fig. 7 Box-Whiskers plots of the Renovation Cases ranked by energy demands during a calculation period of 30 years.

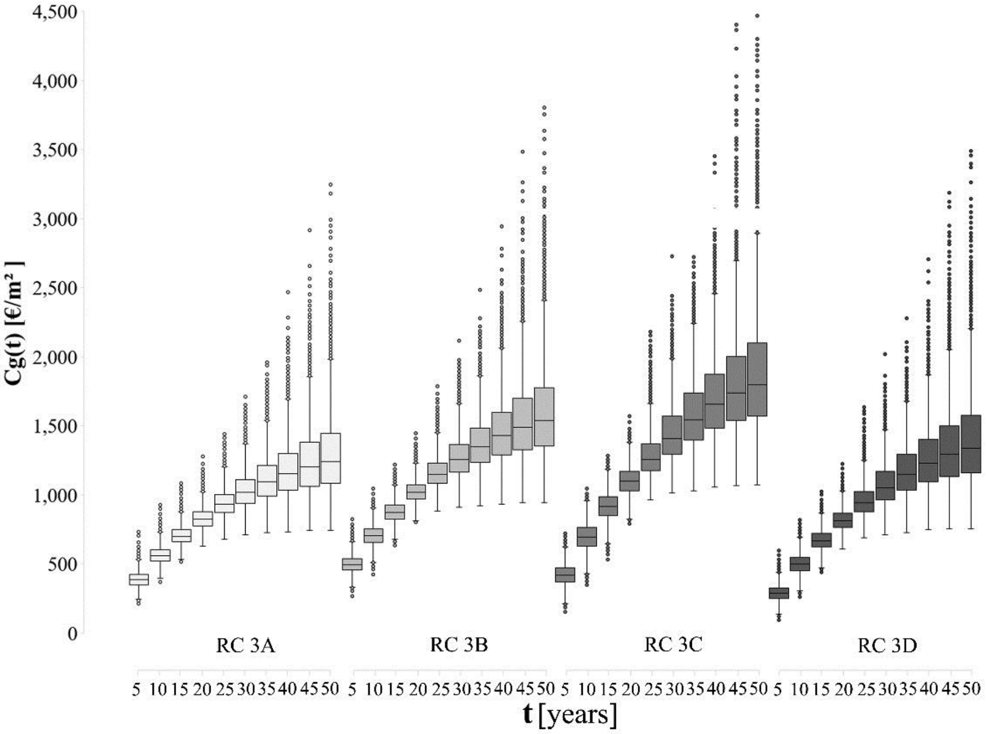
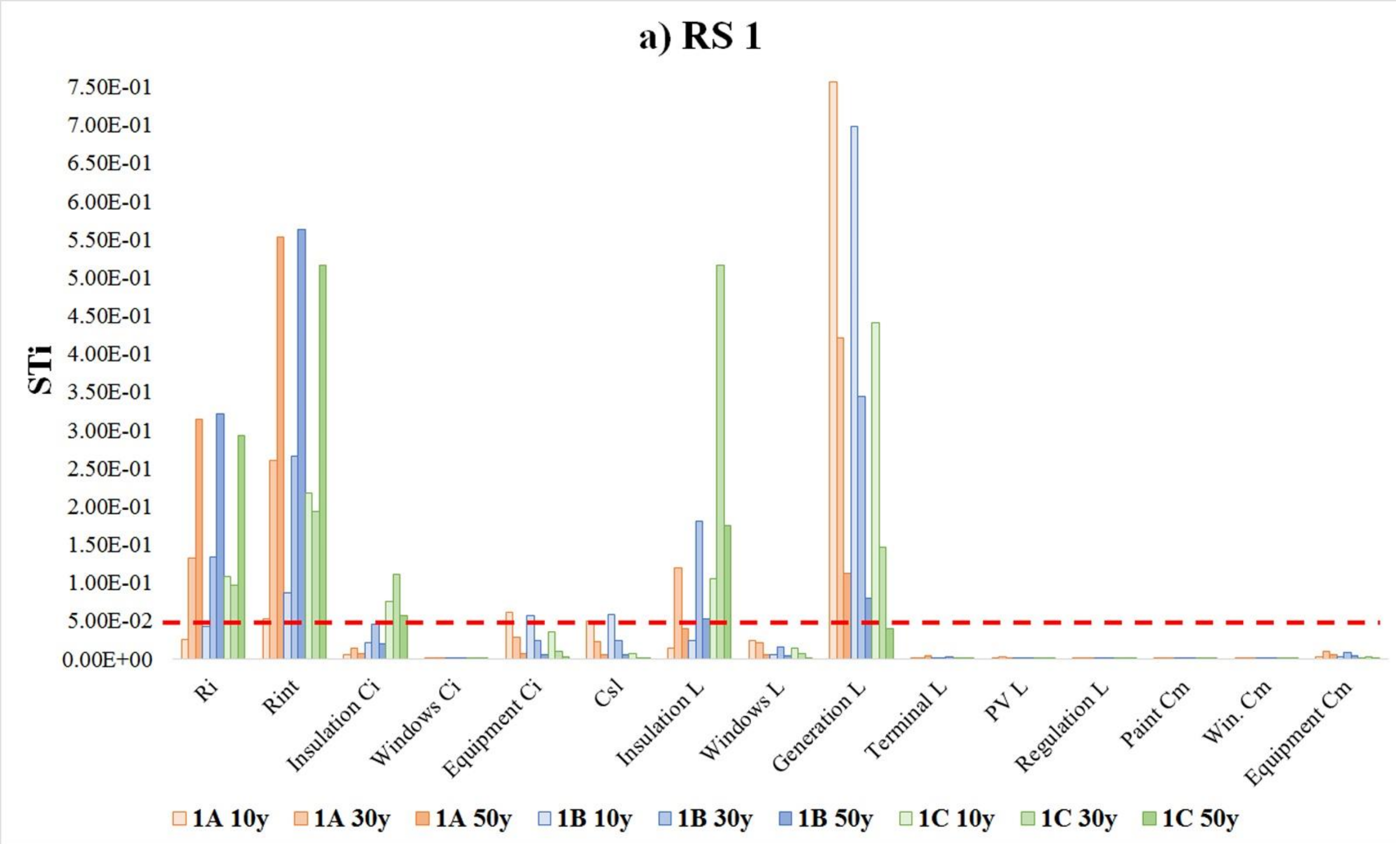
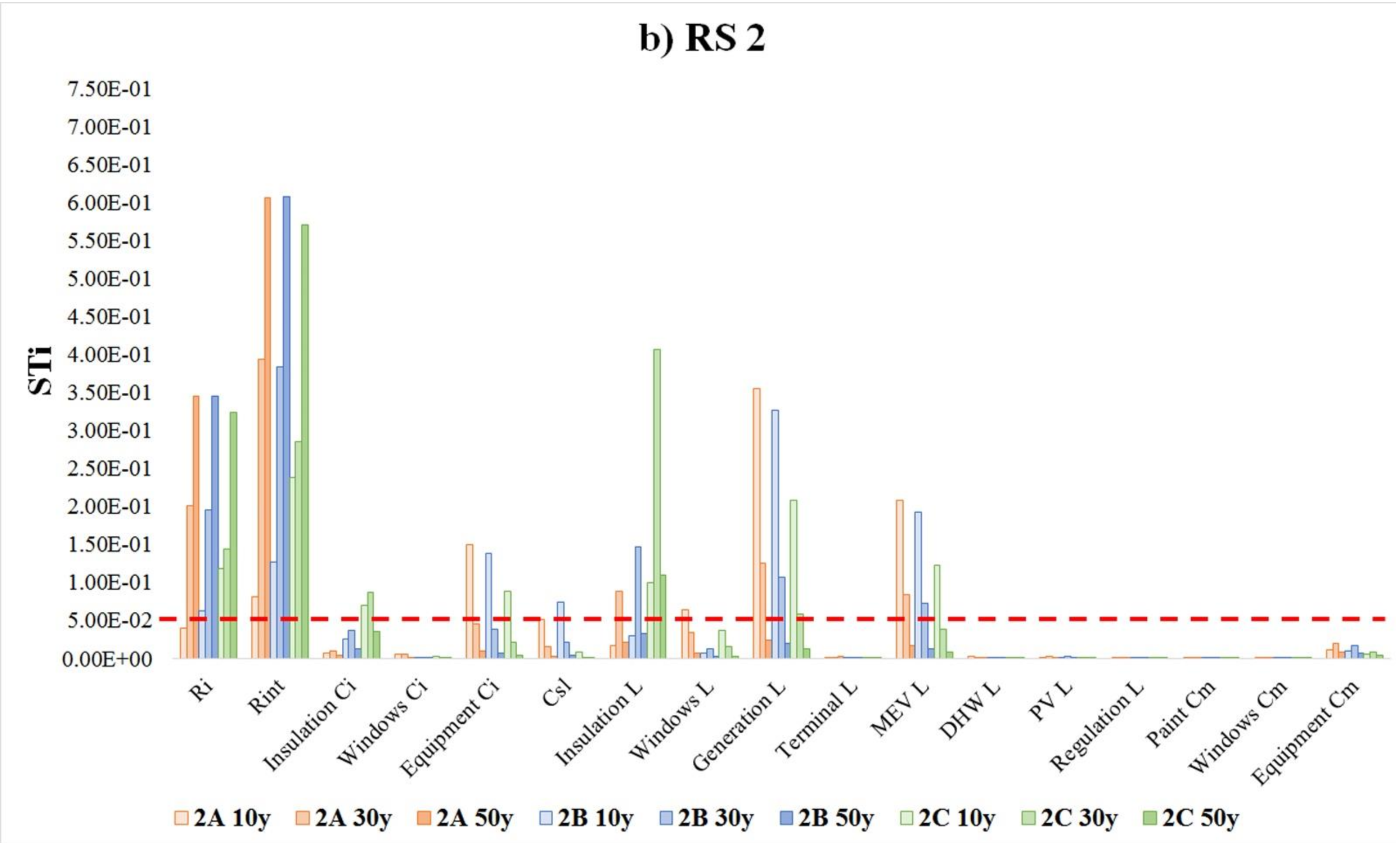


Fig. 8 Probabilistic Global Cost trend (Box-Whiskers plots) for Renovation Scenario 3 (nZEB) during a variable calculation period from 5 to 50 years.


a) RS 1
STi
7.50E-01
7.00E-01
6.50E-01
6.00E-01
5.50E-01
5.00E-01
4.50E-01
4.00E-01
3.50E-01
3.00E-01
2.50E-01
2.00E-01
1.50E-01
1.00E-01
5.00E-02
0.00E+00
Ri
Rint
Insulation Ci
Windows Ci
Equipment Ci
CsI
Insulation L
Windows L
Generation L
Terminal L
PV L
Regulation L
Paint Cm
Win. Cm
Equipment Cm
1A 10y
1A 30y
1A 50y
1B 10y
1B 30y
1B 50y
1C 10y
1C 30y
1C 50y


b) RS 2
STi
7.50E-01
7.00E-01
6.50E-01
6.00E-01
5.50E-01
5.00E-01
4.50E-01
4.00E-01
3.50E-01
3.00E-01
2.50E-01
2.00E-01
1.50E-01
1.00E-01
5.00E-02
0.00E+00
Ri
Rint
Insulation Ci
Windows Ci
Equipment Ci
CsI
Insulation L
Windows L
Generation L
Terminal L
MEV L
DHW L
PV L
Regulation L
Paint Cm
Windows Cm
Equipment Cm
2A 10y
2A 30y
2A 50y
2B 10y
2B 30y
2B 50y
2C 10y
2C 30y
2C 50y

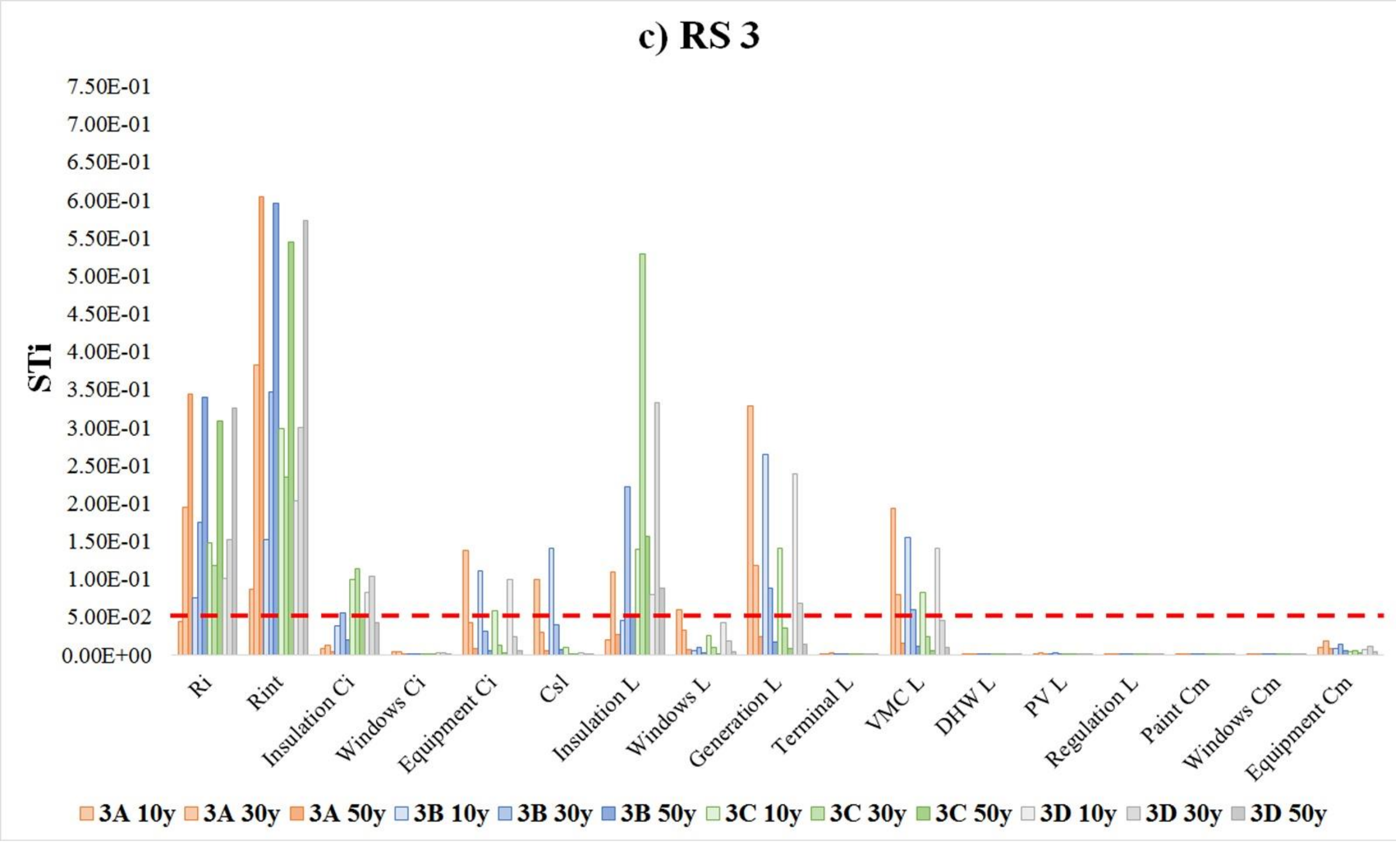


Fig. 9 Total order sensitivity indices for Renovation Scenarios 1 (a), 2 (b), 3 (c), during the calculation periods of 10, 30, 50 years.

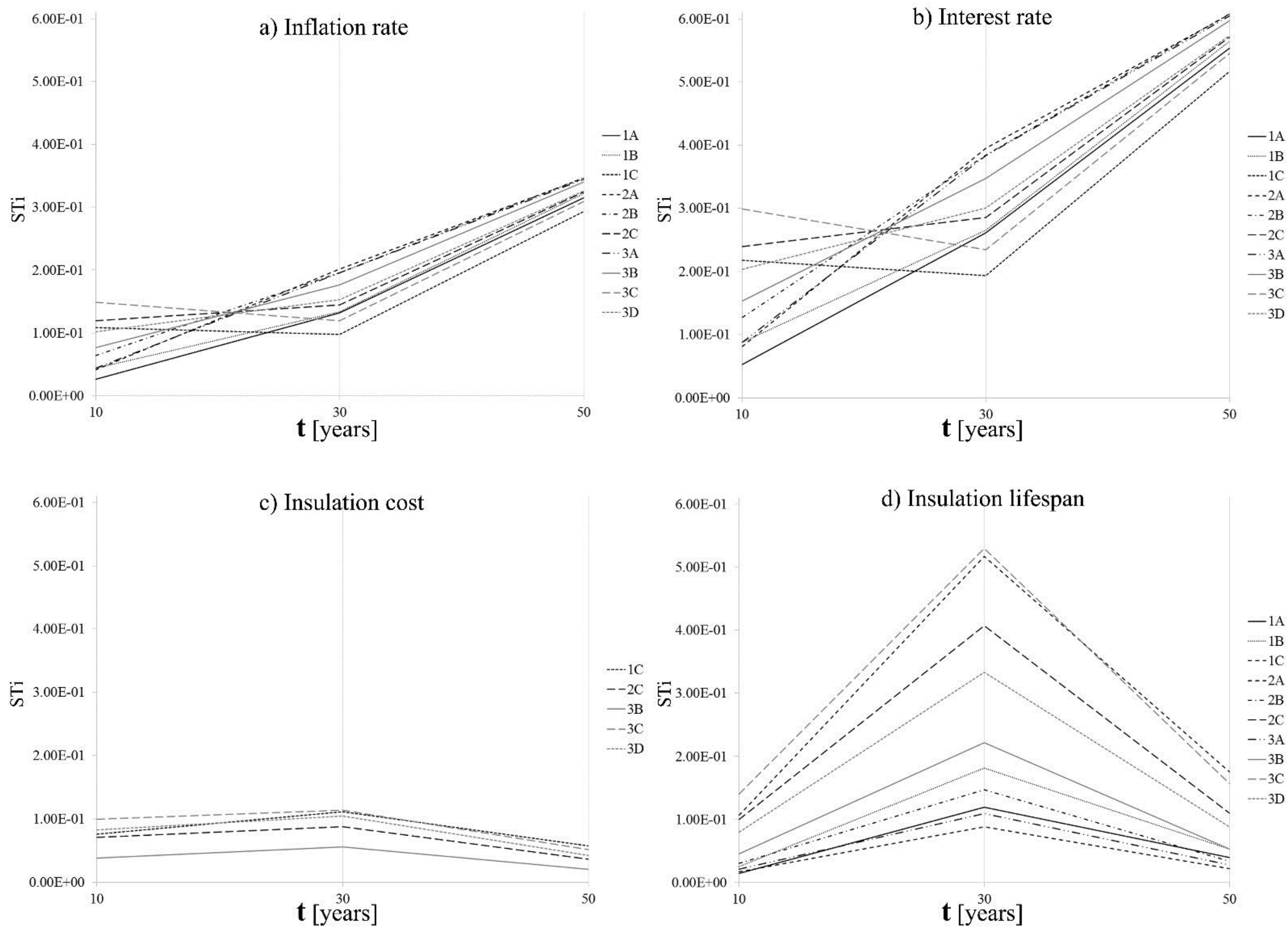


Fig. 10 Total order sensitivity indices of the most influencing input parameters for each renovation case during the calculation periods of 10, 30, 50 years: (a) Inflation rate; (b) Interest rate; (c) Insulation cost; (d) Insulation Lifespan.

Table 1 Main features and costs of the Energy Efficiency Measures related to the three Renovation Scenarios identified for the building case study.

RENOVATION SCENARIO 1

EEM			Unit						
Internal Insulation		solution		XPS		CORK		AEROGEL	
		thickness	[m]	0.11*	0.13**	0.13*	0.13**	0.05*	0.05**
		Uenv	[W/m²K]	0.28	0.25	0.25	0.27	0.24	0.25
		cost	[€/m²]	62.17	67.68	96.64	96.64	318.0	318.0
Windows		solution		PVC frames		wooden-metal frames		PVC frames	
		Uw	[W/m²K]	1.26		1.61		1.26	
		cost	[€/m²]	131.00		335.00		131.00	
Heating and hot water system	Generation	solution		Heat Pump + Solar Collectors (COP =3.89 (35° C); ηmax =0.80 (A= 3.8 m²))					
		cost	[€]	10107.55					
	Terminals	solution		Radiant Floor					
		cost	[€/m²]	72.00					
	Regulation	solution	[€/each]	Direct Digital Control System					
		cost		135.64					
Photovoltaic system		solution		Polycrystalline panels (0.87 kWp)					
		cost	[€]	3731.67					

* related to existing wall thickness 0.29 m
** related to existing wall thickness 0.16 m

RENOVATION SCENARIO 2

EEM			**Unit**						
Internal Insulation		solution		XPS		CORK		AEROGEL	
		thickness	[m]	0.10*	0.13**	0.13*	0.12**	0.04*	0.05**
		Uenv	[W/m²K]	0.30	0.25	0.25	0.28	0.29	0.25
		cost	[€/m²]	59.24	67.68	96.64	92.44	261.3	318.0
Windows		solution		PVC frames		wooden-metal frames		PVC frames	
		Uw	[W/m²K]	0.90		1.61		0.90	
		cost	[€/m²]	180.00		335.00		180.00	
Heating and hot water system	Heating Generation	solution		Condensing Boiler (24kW) - η >0.9					
		cost	[€]	2478.09					
	Hot water Generation	solution		Heat Pump + Solar Collectors (COP =4.03 (35° C); ηmax =0.80 (A= 3.8 m²))					
		cost	[€]	11061.79					
	Terminals	solution		Radiant Floor					
		cost	[€/m²]	72.00					
	Regulation	solution		Direct Digital Control System					
		cost	[€/each]	135.64					
Mechanical extraction ventilation (MEV)		solution		AHU + heat recovery - η >0.93					
		cost	[€]	5452.40					
Photovoltaic system		solution		Polycrystalline panels (1.45 kWp)					
		cost	[€]	5057.77					

* related to existing wall thickness 0.29 m
** related to existing wall thickness 0.16 m

RENOVATION SCENARIO 3

EEM			**Unit**								
Internal Insulation		solution		XPS		CORK		AEROGEL		VIP	
		thickness	[m]	0.16*	0.15**	0.23*	0.12**	0.07*	0.05**	0.02*	0.02 **
		Uenv	[W/m²K]	0.20	0.22	0.15	0.28	0.18	0.25	0.20	0.21
		cost	[€/m²]	76.11	73.31	157.92	92.44	431.5	318.0	193.8	193. 8
Windows		solution		PVC frames		wooden-metal frames		PVC frames		PVC frames	
		Uw	[W/m²K]	0.90		1.61		0.90		0.90	
		cost	[€/m²]	180.00		335.00		180.00		180.00	
Heating and hot water system	Generation	solution		Condensing Boiler (24kW)							
		cost	[€]	2478.09							
	Hot water	solution		Heat Pump + Solar Collectors (COP =4.03 (35° C); ηmax =0.80 (A= 3.8 m²))							
		cost	[€]	11061.79							
	Terminals	solution		Radiant Floor							
		cost	[€/m²]	72.00							
	Regulation	solution		Direct Digital Control System							
		cost	[€/each]	135.64							
Mechanical extraction ventilation (MEV)		solution		AHU + heat recovery							
		cost	[€]	5452.40							
Photovoltaic system		solution		Polycrystalline panels (1.45 kWp)							
		cost	[€]	5057.77							

* related to existing wall thickness 0.29 m
** related to existing wall thickness 0.16 m

Table 2 Uncertain LCC input parameters and related references for standard (deterministic) and probabilistic values.

Category	**Parameters**	**Unit**	**Reference for standard value**	**Reference for distribution**

Economic factors	Inflation rate		[%]	ECB	Time series data fitting
	Interest rate			Bank of Italy [59]	Bank of Italy [59] / EURIRS [60]
Investment costs	Insulation cost		[€]	Producers pricelists	Pricelists variations
	Windows cost				
	Heating plant cost	Generation		Producers pricelists / Italian regional pricelists	Italian regional pricelists variations
		Terminals			
		Regulation			
	MEV				
	PV equipment				
Indirect costs	Indoor surface loss		[€]	Market analysis	range of sales prices/m^2 in surrounding area [63]
Components Lifespan	Insulation lifespan		[years]	INIES database [64]	Authors' judgment
	Windows lifespan			INIES database [64] / Literature [65,66]	Literature [65,66,67]
	Heating plant lifespan	Generation		EN 15459 [33]	ASHRAE database [68]
		Terminals		Producers technical data sheets	Authors' judgment
		Regulation		EN 15459 [33]	ASHRAE database [68]
	MEV			EN 15459 [33]	ASHRAE database [68]
	PV equipment			Producers technical data sheets	Authors' judgment
Operating costs	Paint maintenance		[€]	Market analysis	Labour cost geographic variations [61]
	Windows maintenance				
	Heating plant maintenance			EN 15459 [33] / Market analysis	

Table 3 (a) Probability Density Functions of the stochastic input parameters of the Global Cost calculation (Renovation Scenarios 1 and 2)

Category	Parameters		Unit	Standard Value			Probability Density Function		
				RENOVATION SCENARIO 1					
				1A	**1B**	**1C**	**1A**	**1B**	**1C**
Economic factors	Inflation rate		[%]	1.9			Nor (0.019,0.010439)		
	Interest rate			4.09			Tri (0.0149,0.0908,0.0409)		
Initial investment costs	Insulation cost		[€]	20688	28074	72498	Uni (18122,23253)	Uni (23049,33099)	Uni (60535,84460)
	Windows cost			2583	6343	2583	Uni (2067,3100)	Uni (5373,7314)	Uni (2067,3100)
	Heating and hot water equipment cost	Generation		10108			Uni (8359,11856)		
		Terminals		10224			Uni (8455,11993)		
		Regulation		407			Uni (337,477)		
	Photovoltaic system			3732			Uni (3086,4377)		
Indirect costs	Indoor surface loss		[€]	19654	22111	10134	Uni (15840,23469)	Uni (17820,26402)	Uni (8167,12101)
Lifespan factors	Insulation lifespan		[years]	30			Uni (20,40)		
	Windows lifespan			25	40	25	Wei (1.865325,27.43125)	Wei (3.53,46.59)	Wei (1.865325,27.43125)
	Heating and hot water equipment lifespan	Generation		18			Wei (1.818,15.575)		
		Terminals		50			Uni (35,65)		
		Regulation		20			Wei (1.8655,27.5869)		
	Photovoltaic system			25			Uni (17,32)		
Operating costs	Paint maintenance		[€/y]	232			Uni (207,257)		
	Windows maintenance			31	259	31	Uni (26, 36)	Uni (228,290)	Uni (26,36)
	Equipment maintenance			644			Uni (525,762)		
				RENOVATION SCENARIO 2					
			[%]	**2A**	**2B**	**2C**	**2A**	**2B**	**2C**
Economic factors	Inflation rate			1.9			Nor (0.019,0.010439)		
	Interest rate			4.09			Tri (0.0149,0.0908,0.0409)		
Initial investment costs	Insulation cost		[€]	20207	27961	63193	Uni (17702, 22713)	Uni (22956,32966)	Uni (52766, 73620)
	Windows cost			3518	6343	3518	Uni (2554,4482)	Uni (5373,7314)	Uni (2554,4482)
	Heating and hot water equipment cost	Heating Generation		6258			Uni (5176,7341)		
		Hot water		7282			Uni (6022,8541)		
		Terminals		10152			Uni (8396,11908)		

		Regulation		407			Uni (337,477)		
	MEV			5452			Uni (4509,6396)		
	Photovoltaic system			5058			Uni (4183,5933)		
Indirect costs	Indoor surface loss		[€]	18119	22725	10134	Uni (14602,21635)	Uni (18315,27136)	Uni (8167,12101)
Lifespan factors	Insulation lifespan		[years]	30			Uni (20,40)		
	Windows lifespan			25	40	25	Wei (1.865325,27.43125)	Wei (3.53,46.59)	Wei (1.865325, 27.43125)
	Heating and hot water equipment lifespan	Heating Generation		18			Wei (1.818,15.575)		
		Hot water		20			Uni (15,25)		
		Terminals		50			Uni (35,65)		
		Regulation		20			Wei(1.8655,27.5869)		
	MEV			15			Wei (1.8584,19.5164)		
	Photovoltaic system			25			Uni (17,32)		
Operating costs	Paint maintenance		[€/y]	232			Uni (207,257)		
	Windows maintenance			42	259	42	Uni (36,48)	Uni (228,290)	Uni (36,48)
	Equipment maintenance			1035			Uni (845,1225)		

Table 3 (b) Probability Density Functions of the stochastic input parameters of the Global Cost calculation (Renovation Scenario 3)

Category	Parameters		Unit	Standard Value				Probability Density Function			
				RENOVATION SCENARIO 3							
				3A	**3B**	**3C**	**3D**	**3A**	**3B**	**3C**	**3D**
Economic factors	Inflation rate		[%]	1.9				Nor (0.019,0.010439)			
	Interest rate			4.09				Tri (0.0149,0.0908,0.0409)			
Initial investment costs	Insulation cost		[€]	23125	38008	91104	52688	Uni (20258, 25993)	Uni (31205,44812)	Uni (76072, 106136)	Uni (42150, 63226)
	Windows cost			3518	6343	3518	3518	Uni (2554,4482)	Uni (5373,7314)	Uni (2554,4482)	Uni (2554,4482)
	Heating and hot water equipment cost	Heating Generation		6258				Uni (5176,7341)			
		Hot water		7282				Uni (6022,8541)			
		Terminals		10008				Uni (8277,11739)			
		Regulation		407				Uni (337,477)			
	MEV			5452				Uni (4509,6396)			
	Photovoltaic system			5058				Uni (4183,5933)			
Indirect costs	Indoor surface loss		[€]	26104	34702	13205	6142	Uni (21038,31170)	Uni (27968 ,41437)	Uni (10643,15768)	Uni (4950,7334)
Lifespan factors	Insulation lifespan		[years]	30				Uni (20,40)			
	Windows lifespan			25	40	25	25	Wei (1.8653,27.431)	Wei (3.53,46.59)	Wei (1.8653,27.43)	Wei (1.8653,27.43)
	Heating and hot water equipment lifespan	Heating Generation		18				Wei (1.818,15.575)			
		Hot water		20				Uni (15,25)			
		Terminals		50				Uni (35,65)			
		Regulation		20				Wei (1.8655,27.5869)			
	MEV			15				Wei (1.8584,19.5164)			
	Photovoltaic system			25				Uni (17,32)			
Operating costs	Paint maintenance		[€/y]	232				Uni (207,257)			
	Windows maintenance			42	259	42	42	Uni (36,48)	Uni (228,290)	Uni (36,48)	Uni (36,48)
	Equipment maintenance			1032				Uni (842,1222)			

Table 4 Main results of the energy performance assessment of the Renovation Cases.

RCs	1 A	1B	1 C	2 A	2 B	2 C	3 A	3 B	3 C	3 D
Geometrical Data										
Heated usable floor area [m²]	140.8	140.0	143.9	141.3	139.8	143.9	138.7	135.9	142.9	145.2
Gross heated volume [m³] Vg	646.4	646.9	646.6	646.8	640.0	637.1	646.4	640.2	637.9	640.0
Thermal dispersion surface [m²] S	399.4	396.1	401.9	401.9	400.6	397.5	398.8	401.7	398.4	398.0
S/Vg	0.62	0.61	0.62	0.62	0.63	0.62	0.62	0.63	0.62	0.62
Annual energy from RES										
PV [kWh]	590	837	593	1340	1465	1465	1340	1464	1465	1465
Solar collector [kWh]	2163	2224	2175	2238	2233	2250	2237	2225	2250	2258
Annual energy consumption										
Electricity [kWh]	3904	3786	3760	3076	2901	2862	2443	2321	2222	2273
Gas [Nm³]	0.0	0.0	0.0	38.9	37.6	40.1	37.9	35.4	40.3	41.5
Energy needs										
H'T [W/(m²K)]	0.38	0.38	0.37	0.38	0.37	0.37	0.31	0.31	0.33	0.35
EPH,nd [kWh/(m² y)]	64.00	62.90	60.11	58.17	58.29	56.47	49.11	50.21	47.27	47.64
Primary energy										
EPH,nren [kWh/(m² y)]	49.16	48.76	46.83	33.06	31.06	30.03	24.58	24.16	23.11	23.66
EPH,ren [kWh/(m² y)]	15.30	15.36	14.71	11.92	12.04	11.63	9.47	10.05	9.78	9.90
EPgl,nren [kWh/(m² y)]	53.50	52.78	51.37	50.76	47.68	46.99	41.13	39.83	39.88	40.64
EPgl,ren [kWh/(m² y)]	36.51	37.30	36.04	41.54	41.66	40.69	39.21	40.42	43.18	40.89
EPgl,tot [kWh/(m² y)]	90.01	90.08	87.41	92.30	89.34	87.68	80.33	80.25	83.06	81.53

Table 5 Total order sensitivity indices for each renovation case during a calculation period of 30 years.

		1A	1B	1C	2A	2B	2C	3A	3B	3C	3D
Economic Parameters	Inflation Rate	**1.32E-01**	**1.34E-01**	**9.77E-02**	**2.02E-01**	**1.95E-01**	**1.45E-01**	**1.96E-01**	**1.76E-01**	**1.19E-01**	**1.53E-01**
	Interest Rate	**2.61E-01**	**2.66E-01**	**1.94E-01**	**3.95E-01**	**3.85E-01**	**2.85E-01**	**3.83E-01**	**3.47E-01**	**2.35E-01**	**3.01E-01**
Initial investment costs Parameters	Insulation cost	1.46E-02	4.58E-02	**1.11E-01**	1.08E-02	3.72E-02	**8.77E-02**	1.34E-02	**5.62E-02**	**1.14E-01**	**1.05E-01**
	Windows cost	1.42E-03	1.31E-03	4.97E-04	5.59E-03	1.07E-03	2.62E-03	5.28E-03	8.77E-04	1.64E-03	3.07E-03
	Equipment Costs	2.94E-02	2.40E-02	1.03E-02	4.57E-02	3.93E-02	2.14E-02	4.28E-02	3.19E-02	1.33E-02	2.49E-02
Indirect Costs Parameters	Indoor surface loss	2.39E-02	2.47E-02	2.23E-03	1.58E-02	2.13E-02	2.31E-03	3.09E-02	4.07E-02	2.45E-03	9.93E-04
Lifespan Parameters	Insulation Lifespan	**1.20E-01**	**1.81E-01**	**5.17E-01**	**8.87E-02**	**1.47E-01**	**4.07E-01**	**1.10E-01**	**2.22E-01**	**5.30E-01**	**3.33E-01**
	Windows Lifespan	2.13E-02	1.56E-02	7.45E-03	3.48E-02	1.27E-02	1.63E-02	3.29E-02	1.04E-02	1.02E-02	1.91E-02
	Generation Lifespan*	**4.21E-01**	**3.44E-01**	**1.48E-01**	**1.25E-01**	**1.08E-01**	**5.87E-02**	**1.18E-01**	**8.83E-02**	3.67E-02	**6.88E-02**
	Terminals Lifespan	2.13E-03	1.74E-03	7.45E-04	1.63E-03	1.40E-03	7.62E-04	1.49E-03	1.11E-03	4.63E-04	8.68E-04
	MEV Lifespan	-	-	-	**8.50E-02**	**7.31E-02**	3.97E-02	**8.02E-02**	**5.98E-02**	2.49E-02	4.66E-02
	Hot water Lifespan	-	-	-	2.24E-03	1.93E-03	1.05E-03	2.12E-03	1.58E-03	6.56E-04	1.23E-03
	PV Lifespan	2.68E-03	2.19E-03	9.39E-04	3.83E-03	3.29E-03	1.79E-03	3.61E-03	2.69E-03	1.12E-03	2.10E-03
	Regulation Lifespan	5.20E-04	4.25E-04	1.82E-04	4.04E-04	3.47E-04	1.89E-04	3.81E-04	2.84E-04	1.18E-04	2.21E-04
Maintenance Parameters	Paint Maintenance	4.64E-04	3.79E-04	1.63E-04	3.61E-04	3.10E-04	1.69E-04	3.41E-04	2.54E-04	1.06E-04	1.98E-04
	Windows Maintenance	1.62E-05	5.87E-04	5.67E-06	2.29E-05	4.80E-04	1.07E-05	2.16E-05	3.93E-04	6.69E-06	1.25E-05
	Equipment Maintenance	1.04E-02	8.49E-03	3.64E-03	2.09E-02	1.79E-02	9.75E-03	1.96E-02	1.46E-02	6.06E-03	1.14E-02

* for Renovation Scenario 1: Heating + hot water generation